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A FULLY COUPLED, AUTOMATED FORMATION CONTROL SYSTEM FOR DISSIMILAR AIRCRAFT IN MANEUVERING, FORMATION FLIGHT

THESIS

Paul R. Rohs, Captain, USAF

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THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Electrical Engineering

Paul R. Rohs, B.S.
Captain, USAF

March 1991

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Preface

The objective of this study was to develop and simulate a formation control system, capable of controlling a number of like or dissimilar aircraft in maneuvering, formation flight. The concept is applicable to high workload formation flights such as mixed formations of Special Operations Forces. Aircraft formations are controlled as entities themselves, with inner loops of individual aircraft in the same sense as aircraft are controlled with inner loops of pitch, roll and yaw. The entire project placed emphasis on a simplistic, but realistic approach to system design and simulation. Formations of mixed aircraft are simulated and perform adequately by the simple control structure and strategy developed herein.

I am deeply indebted to my advisor, Dr J. J. D'Azzo, for his expertise and guidance in all aspects of this research. I owe special thanks to personnel at the Flight Dynamics Laboratory who sponsored this research, for their support and our lengthy conversations about what is really important. I am also thankful for all the individuals and organizations whose assistance I received in developing the aircraft and formation models. A special thanks to all the pilots who contributed their experience in flying the aircraft I used in the study.

Finally and most importantly, to my parents, Richard and Ruth, to whom I dedicate this effort, who thoughtfully neglected teaching me there were things I couldn't accomplish. And perhaps more importantly, to my wife Jonnie, who put up with me and helped me through it.

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Symbols And Notation

A	altitude
AGL	above ground level
Az	azimuth angle
C	subscript for commanded value
CC	subscript for controlled commanded input
dx	longitudinal separation distance
dy	lateral separation distance
dz	vertical separation distance
deg	degree
El	elevation angle
$\underline{FC}$	input formation control vector
FLIR	forward looking infrared
ft	feet
G_A	altitude (z) channel gain
G_H	heading (y) channel gain
$G_{Ix/y}$	integral path gain (x or y axis)
$G_{Px/y}$	proportional path gain (x or y axis)
G_V	velocity (x) channel gain
H	magnetic heading
kt(s)	knot(s)
L	subscript for lead aircraft
l	subscript for lead aircraft (used in tables)
m	minute
max	maximum
NVG	night vision goggles
PI	proportional plus integral
r	absolute (line of sight) range
$r_{\#}$	range from wing position # from the lead aircraft
r_W	range from wing position 1 from wing position 2
SOF	special operations forces
TF	terrain following

TRN	terrain referenced navigation
W#	pertaining to wing position #
W	subscript for wing aircraft
x	longitudinal axis
y	lateral axis
z	vertical axis

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Abstract

This study developed a fully automated formation control system, capable of controlling a number of like or dissimilar aircraft in maneuvering formation flight. C-130 fixed wing aircraft and H-53 helicopters were modelled in various formations and simulated through a mix of maneuvers. External formation guidance was assumed as a single data burst of nominal formation guidance commands and separation distances for each wing aircraft in the formation. No communication was assumed between formation aircraft. Wing aircraft tracked lead aircraft maneuvering with an ideal on-board sensor, maneuvering to maintain relative position. It was determined that lead aircraft inputs must be attenuated at times to prevent less capable wing aircraft from being outmaneuvered. A simple proportional plus integral feedback controller was used to add control to the lead aircraft, or nominal formation, commands. This allowed aircraft with differing operational capabilities to safely and effectively execute all maneuvers evaluated in the study. C-130 aircraft models were used for the initial developement. H-53 models were later inserted into the final design to evaluate system and design robustness. The system is shown to operate independent of the aircraft or formation configuration being flown. Open loop and controlled responses are presented for comparison.

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I INTRODUCTION

1.1 Overview

The introduction and background to the problem considered in this research is provided in Chapter I. Additional background on operational aspects of the problem and requirements for its solution are presented in Chapter II. Technical aspects, control theory background, and simulation model development of individual aircraft and formation models are described in Chapter III. Basic open loop performance of these models is also presented in Chapter III, as are requirements for additional control. A design for the required formation system controller is developed in Chapter IV. A thorough evaluation of final formation control system performance for both fixed wing C-130 aircraft and H-53 helicopters is presented in Chapter V. Overall conclusions for this research and areas requiring further study are presented in Chapter VI.

1.2 Background

Air Force responsibilities require forces and equipment capable of performing a vast number of different roles and missions. Air Force structure is organized vertically and laterally around these different missions and capabilities. Operations are based on the ability to maintain, train, equip, and fly aircraft in support of these many different requirements. Air Force flying missions vary from observation to air-to-air combat and back to cargo and personnel transport. While

technology has increased effectiveness and safety of all aspects of these missions by expanding aircraft system capabilities, it has also increased their complexity.

An ill effect, directly tied to this increase in technology and complexity, is an imposed increase in pilot workload in performing his tasks and missions. Some airborne systems require so much pilot attention that the system is unusable in the particular environment for which the system was designed. Flying the aircraft can never take a back seat to operating an on-board system, for whatever reason. A well known example of this is a Vietnam era aircraft missile warning system. In the heat of air combat, pilots turned off their missile warning systems because there was just too much going on, to also concentrate on the warning tones emitted by that particular system.

A flight regime that requires constant vigilance by the pilot is low level flight in any aircraft, and even worse if flown in formation with other aircraft. This type of mission is frequently flown by Air Force Special Operations Forces (SOF). The following unclassified description describes in generic terms, requirements placed on these pilots.

> Air Force Special Operations Forces (SOF) are tasked to conduct missions world-wide, across the spectrum of conflict, using highly diverse tactics based on the specific scenario. These missions can be overt, clandestine, or covert, depending on the situation, and can range from highly sensitive missions of national importance to day-to-day operations and training. These missions emphasize concealment and secrecy and many times require long range penetration behind enemy lines. To reduce the probability of their detection, these missions are primarily carried out at night and flown at very low altitudes. Frequently, these operations require multi-aircraft formations between like or dissimilar aircraft. For example, a formation of several helicopters may be used to achieve the required mass for infiltration or exfiltration of

troops; MC-130 formations may be used to conduct multiship airdrops of troops and equipment; HC-130 formations may be used when several helicopters are to be refueled; and gunships may fly in formation with other aircraft in the event that threat suppression is required. (21:11)

Clearly these requirements impose a tremendous work-load on pilots flying rotary or fixed wing aircraft. Their range of operations and operating conditions allow little room for error, so any pilot assistance in safely executing their mission is invaluable.

For these operations, a great deal of flexibility is required of the pilots, tactics, and aircraft employment. Pilots and equipment must be capable of a myriad of mission profiles with short notice, anywhere, anytime, in any weather, and be assured of a very high probability of success, and normally with no outside assistance. A formation is usually left on its own, except for possible enroute refuelling. Once they are gone, they're on their own and must handle any contingencies accordingly.

With today's sensors, system capabilities, and control design technology, all possible pilot and mission aids should be exploited in support of this demanding mission requirement.

1.3 Problem Statement

A formation control system is developed in this thesis to control a number of like or dissimilar aircraft in maneuvering, formation flight. System operation is then evaluated through computer simulation.

The project entails both qualitative and quantitative aspects. Qualitatively, basic control strategy and system structure are developed

based on realistic operational requirements. Realistic system operation is useable on formations representative of pertinent Air Force missions and flight conditions. The control strategy meets pilot acceptability criteria and inherent control theory restrictions. Quantitatively, accurate mathematical and computer models of the aircraft, formations and overall formation control system are developed. Standard control system design techniques are used in order to instill confidence in the findings. Results are presented in understandable and sufficient detail to be meaningful.

This research breaks ground in several areas, as the idea of a flight control system is taken to a higher level. A flight control system, in a classical sense, is a system which receives an input, either from a pilot or automated system, and translates that input into a change in an aircraft's flight condition. These changes are caused by variations in aircraft configuration through effectors which alter control surface positions, power settings, or other factors. These effectors are controlled by inner system control loops, such as for roll or speed control. In short, a typical flight control system effects a desired change in an aircraft's flight condition, based on some desired input.

This research, however, expands that concept by adding a system level around multiple aircraft in formation. These aircraft in effect, constitute inner loops of a formation level control system. Standard control system theory still applies, but at a higher level.

1.4 Development of Formation Flight Technology

1.4.1 Early Low Level Formation Flight Studies. During the Vietnam era, several extensive studies sponsored by the Army looked in detail at how helicopter formation missions were accomplished. References 1 and 20 examine requirements and capabilities needed for safe, successful execution of night, helicopter formation missions. Both studies used extensive interview data from pilots experienced in this type of mission. Operational aspects of the missions and their requirements were studied.

> Detailed interviews with experienced Army helicopter pilots having night formation flight experience in Vietnam clearly show that the night assault mission is the principal and most important helicopter night formation mission currently performed in Southeast Asia. These preplanned operations typically involve a formation of 5 to 10 UH-1D/H troop-carrying helicopters. (1:33)

Reference 1 concentrates on human factors aspects of helicopter night formation flight and established a baseline of visual requirements for these operations in Southeast Asia. Typical missions were analyzed in terms of gross pilot tasks, cues and reference frames used by pilots during the missions. It was determined that these missions could not be accomplished without adequate visual cues (1:33). The study evaluated several night vision system options in terms of capabilities, merits, constraints and shortcomings (1:1) as a pilot assist for these missions.

Since pilots required constant visual contact with other aircraft in the formation, aircraft spacing was somewhat driven by their need to see each other. Formation spacing is normally loose during cruise portions of the mission, while tighter formations with tip-to-tip separations of three to four rotor diameters (1:34) were employed for terminal and landing

approach mission segments. In poor visibility environments, closer formation spacings are required. These visibility requirements are just the opposite of those desired in terms of avoiding the enemy. In short, pilots want to be able to fly in poor weather, but do not want to fly close formations in that weather.

An earlier study, also sponsored by the Army during the mid 1960's, developed requirements for an all-weather Army aircraft landing system. One task considered preliminary results of this study, applied to formation flight (20:1). This study of operational aspects such as aircraft characteristics, meteorological environment, tactics and formations led to formation flight requirements which differed from those of the landing system. One important difference was that a formation typically operates over a much smaller distance than a landing system, which therefore allows for a simpler, more covert means of communication.

> It is also observed that the ability of helicopters (one type of aircraft of interest in this study) to hold their positions in the presence of atmospheric turbulence will have an important influence on aircraft spacing within a formation and on sensor accuracy requirements and data rates. (20:7)

Recent programs have also considered these problems inherent in formation flight, but concentrated on pilot situational awareness. Additional displays and display methods help the pilot know where he and other formation aircraft are located, but little assistance is provided the pilot in actually controlling or positioning the aircraft. Current autopilots handle high altitude, loose formation flying and station-keeping, but not close-formation, maneuvering flight. This research applies to the area of close, maneuvering, formation flight. An extensive

review of these early studies is used in developing the system in order to produce realistic results.

Past studies have also considered techniques for controlling an unmanned aircraft from a manned aircraft. These Auto- or Robotic-Wingman studies are used to determine what control strategies can best accomplish this task. Pilot techniques for this type of mission are also studied. From this qualitative background, a realistic control strategy and system structure is developed.

1.4.2 Drone Formation Control Systems. The Air Force and Navy have both accomplished work in automated formation control of drone aircraft. As early as 1963, the Navy demonstrated a capability of controlling two QF-9, full scale, drone aircraft in formation flight with each aircraft controlled by a separate controller. The requirement was to present a realistic threat formation of aircraft for missile weapon development (10:4). The wing (or slave) aircraft was maneuvered by its controller in order to keep the lead (or master) aircraft in the center of a TV screen. This system was limited to formations of two aircraft due to coordination difficulties and the inability of fine adjustments on the QF-9 aircraft's discrete control system.

The U. S. Army Missile Command contracted with IBM in the mid seventies to build a drone formation control system capable of controlling a number of drone aircraft simultaneously in formation. Numerous tests were flown at White Sands Missile Range over the years to evaluate various system capabilities. Mission scenarios included take-off, multiple missile attack evasions and full stop landings. The system operated

adequately in all modes. This system used full scale PQM-102 aircraft specially modified to operate with automated control system equipment. Pilots could also go along for the ride as observers and safety pilots, to override the system in the event of system failure. The control system was also successfully applied to formations of unmanned Army tanks operating in formation. (9)

The Air Force is also currently operating a drone control system as part of the test facilities at Eglin Air Force Base. The Gulf Range Drone Control Update System (GRDCUS) is in use today.

1.4.3 Current State of Formation Flight Technology. Special Operations Forces (SOF), currently use Night Vision Goggles (NVGs), Forward Looking Infrared (FLIR) devices, and various Terrain Following (TF) systems which allow close formation operations during penetration and terminal mission phases. Each device or system, however, has inherent limitations restricting operations due to visual conditions, as the pilot is still responsible for manually positioning the aircraft. This increases the chance of midair collision or impact with terrain, vegetation, or other obstructions (21:11). In all, formation flight is performed today by pilots who may have visual enhancement systems, but who still must manually control their aircraft in all axes, again, based on visual inputs during these operations.

1.5 Research Objectives

The overall objective of this research, as stated in 1.2, is to develop a formation control system capable of controlling a number of like or dissimilar aircraft in maneuvering, formation flight, and to evaluate

system operation and performance through computer simulation. In support of this goal, several additional sub-objectives are involved in the particular system developed.

--- A formation control system such as proposed, must be robust in providing safe, positive control, as well as flexibility to allow formation aircraft to exchange positions, or the formation configuration itself, as required.

--- In addition to controlling overall formation maneuvering, a formation control system must insure that individual aircraft remain separated during required maneuvering.

--- Formation maneuvering must be limited at times so as not to exceed the capabilities of any member of the formation.

--- The system is to be designed in a modular sense in order to be independent of the particular aircraft flown in the formation. This also allows aircraft position changes within the formation without system reconfiguration.

1.6 Research Procedures

A review of background information, some of which is discussed in previous sections, is presented in order to show how formation flight is currently accomplished. Tactics, methods, and dangers of formation flight form the basis of this fully coupled, automated system design and its operation in order to insure pilot acceptance.

Representative computer models and simulations are developed based on realistic and pertinent Air Force requirements. Appropriate combinations of aircraft, formations, maneuvers, and capabilities are included in the final simulation.

Control system design is accomplished using classical control design techniques. Design and simulation results are accurately represented, as well as the process through which they were achieved.

1.7 Operational Aspects of Research

A formation control system such as proposed, has a potentially major impact on formation flight operations with inherent high pilot workload. A typical mission may require low level, covert, close formation flight, by dissimilar aircraft such as heavily loaded C-130 gunships with more lightly loaded C-130 tankers or troop carriers. This type of mission is often flown by the Special Operations Forces (21:11). Another possible formation is one of H-53 helicopters which also differ from each other in operating capabilities. One helicopter may be limited in maneuverability by the capability of an advanced terrain following navigation system, while other formation members may only be limited by aircraft limits. The worst case formation is one of H-53 helicopters during refueling by C-130 tanker aircraft. These types of missions inherently have extremely high levels of pilot workload. Any assistance available to them would greatly increase mission effectiveness and safety.

The particulars of this study, in terms of aircraft, formations, and maneuvers to be considered, reflect typical unclassified Special Forces missions. Two aircraft used by SOF are considered for this research.

C-130 fixed wing aircraft and H-53 helicopters are used and represent the workhorses for SOF units. Two models of each aircraft, with different flight characteristics due to some limitation such as aircraft system limitations or gross weights, are used during simulation.

Several different formations, representative of different portions of a typical SOF mission, are studied. Formations of two and three like or dissimilar aircraft are flown in trail and diamond formations to be described in the next section. The worst case formation, H-53 helicopters in formation with C-130 fixed wing aircraft is not considered. This formation is only flown during refuelling and in a non-maneuvering manner. Formations of C-130 fixed wing aircraft are used for system development, H-53 helicopters are then inserted into the formation models in order to evaluate system design robustness.

A limited mix of maneuvers is used for system evaluation. Formations are simulated through a heading change or flat turn, a terrain or obstruction clearing maneuver (such as a ridge-crossing), and a change in formation (such as from the diamond formation to a trail formation and reverse). This combination of formations and maneuvers provides a broad base from which the merit of such a formation control system becomes clear.

1.8 Formations

Diamond and trail formations are employed during this research. Some version of diamond or 'V' formation, as shown in Figure 1, is often used for cruise portions of a mission (1:34). This configuration allows good relative visibility between formation aircraft. The trail formation

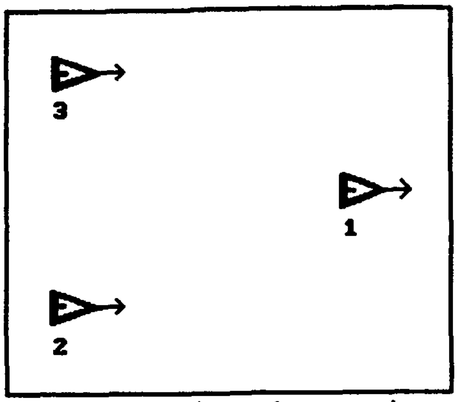

Figure 1 Diamond Formation Pattern

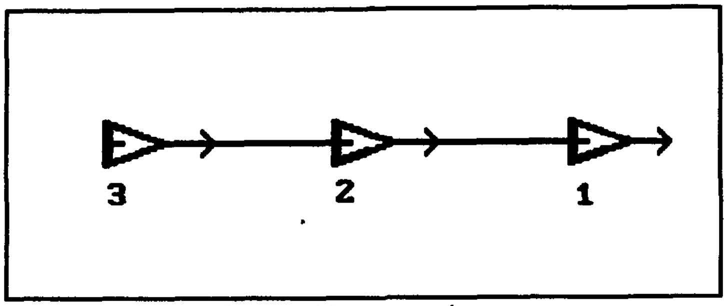

Figure 2 Trail Formation Pattern

shown in Figure 2 is sometimes used during a turn or threat/terrain clearing, such as flying through a valley or choke-point which is only wide enough for single file formations (1:56). Trail formations are important with regard to covert operations as the minimum amount of landmass is overflown. This may translate to a reduced probability of interception by ground forces.

1.9 Maneuvers

Three separate maneuvers are executed during this study. Maneuvers include a formation turn or heading change, a terrain clearing maneuver such as a ridge crossing, and a change in formation from diamond to trail formation and return to diamond. Maneuvers are executed individually and

not in combinations. Initial conditions for all maneuvers are straight, level, unaccelerated flight in a constant formation.

1.9.1 <u>Heading Change</u>. This maneuver is basically a flat formation turn. Depending on the formation being flown during the turn, different actions must be taken by the pilots in order to maintain formation during the maneuver. Based on formation geometry, these differences become obvious through inspection. The trail formation requires each pilot to merely follow the aircraft in front of him as shown in Figure 3.

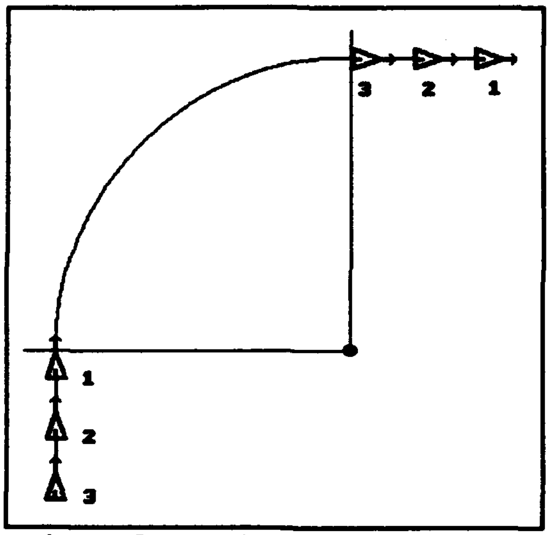

Figure 3 Heading Change in Trail Formation

In a diamond formation, shown in Figure 4, the maneuver becomes more complex. The inside and outside formation aircraft must reduce and increase their velocities respectively, in order to maintain relative position. Figure 4 clearly shows the amount of change is dependent on formation geometry and the magnitude of the heading change.

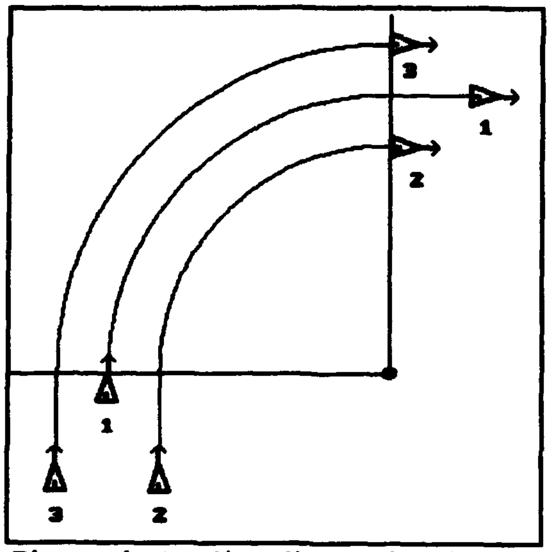

Figure 4 Heading Change in Diamond Formation.

1.9.2 Ridge Crossing. This terrain clearing maneuver is shown in Figure 5. The formation is initially flying at a constant altitude above terrain. Due to an approaching threat area, obstacle, or terrain feature, the formation must execute a maneuver to climb above the obstacle, and subsequently descend after it is passed. No change in velocity or heading

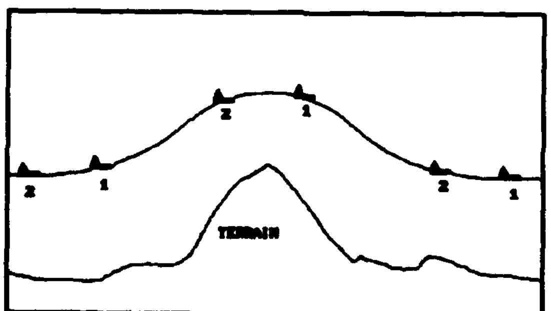

Figure 5 Terrain Clearing Maneuver.

is required, but the formation pattern is to remain constant. This maneuver is the same for either trail or diamond formation. The maneuver includes climb initiation, levelling off, descent initiation, and a final levelling off at the original altitude.

1.9.3 Formation Change. The particular formation flown during a certain mission segment varies. A long cruise portion of the mission may employ a loose diamond pattern, while penetration segments may require a close trail pattern in order to penetrate a narrow threat corridor or valley permitting only single file passage. For whatever reason, formations can change frequently during an average mission to meet changing environments.

Formation change maneuvers are considered for transition from trail to diamond formations, and from diamond to trail as shown in Figure 6 and Figure 7. Details of the maneuver differ by geometry. In going from trail to diamond formations, as shown in Figure 6, wing aircraft must accelerate and turn to pull into a wing position aft and to the side of the lead aircraft. In the opposite transition, from diamond to trail formation, wing aircraft must decelerate and drop further behind the lead aircraft and pull in behind the lead as shown in Figure 7.

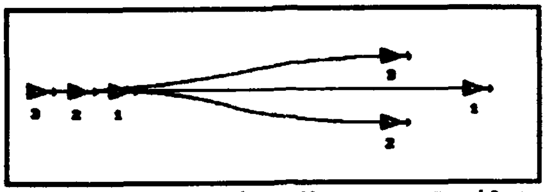

Figure 6 Formation Change - Trail to Diamond

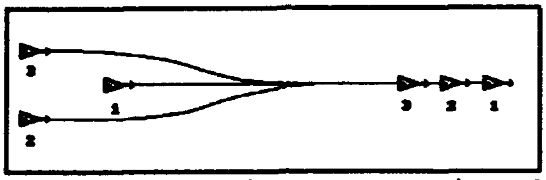

Figure 7 Formation Change - Diamond to Trail

1.9.4 <u>Other Formations and Maneuvers</u>. The flight conditions in this study include low level flight and maintaining the formation in a heading change as shown in Figure 4. It is recognized that in other situations the formation may not need to be maintained during such a maneuver. For example, fighter aircraft at high altitudes may have wing aircraft move out of the original plane and reverse positions with respect to the lead aircraft. Such maneuvers are not included in this study.

1.10 <u>Control Aspects of Research</u>

A system such as proposed, must be independent of the particular aircraft and their positions in the formation. In order for aircraft of differing flying characteristics to fly together in formation, and to switch positions in that formation, the formation control system must operate regardless of the aircraft in each position. In other words, the system must be self optimizing for each aircraft configuration. The

system must control formation maneuvering while not restricting individual aircraft capabilities to match those of a less maneuverable aircraft.

Formation level control inputs are available to all aircraft and include lead aircraft control inputs and separation distances for each wing aircraft relative to the lead. Formation wing aircraft track lead aircraft maneuvering in order to maintain these target spacings relative to the lead aircraft.

A proportional plus integral (PI) controller is developed for required formation level control. This arrangement, through modification of gains in the proportional and integral paths, essentially decouples system states which are inherently coupled in the system. This will command formation maneuvering, through the lead aircraft, with minimum affect on formation spacings.

Measures of merit are developed to evaluate system performance based on selected criteria to determine how well the system operates, or at least based on flight safety. Detailed development of these measures of merit are addressed in Chapter III. Selected measures of merit lead to format and content for presentation of results obtained. Study results include a thorough evaluation of this formation control system concept. System operation, robustness, and value to pilots is evaluated.

1.11 Simplifying Assumptions

A number of assumptions are required to confine this research to a reasonable effort. In support of the objectives described in Section 1.5, the following assumptions limit the scope of this research.

The actual origin of overall formation guidance is assumed and not addressed as part of this research. It is assumed that formation guidance comes from pre-flight mission planning, on-board sensors, or a combination of both. In an attempt to minimize electronic emissions, no continuous communication or data stream (feed-forward path) is used for guidance between individual aircraft in the formation. Each aircraft receives the overall formation control input vector as a single data burst and operates on their respective parameters from that vector. Details of the control strategy and each aircraft's inputs are described in Chapter III.

As set forth in Section 1.5, this research does not require, and does not attempt to create, exact models of aircraft, formations, or the control system considered for this research. Aircraft simulation models are developed which match overall flight path vector, dynamic responses of the aircraft modelled. Simple first order models are used, as the aircraft models themselves are not the subject of study.

It is assumed that each individual aircraft is capable of automated control to effect flight path control inputs. Each fixed wing aircraft is assumed to use forward velocity to control relative separation along the flight path vector, coordinated turns for lateral separation, and altitude for vertical separation. Although helicopters use different effectors to

control their flight path than fixed wing aircraft, overall flight path changes are the same.

Each aircraft is assumed to possess an on-board sensor capable of providing precise position measurements relative to other formation aircraft. Wing aircraft sensor measurement data is used to track lead aircraft maneuvering, which allows wing aircraft to maintain target separation from the lead. The sensor is assumed ideal in that no time delays, noise, or errors are inserted into these measurements. Specific sensor systems are not addressed in this research, as emphasis is on control strategy and structure, not on particulars or an exact simulation of all aspects of such a system.

1.12 System Simulation and Operation

The initial design and development of simulation models for individual plants and formation models were developed using a Sun workstation version of MatrixX. This system was used for control law verification, block diagram development, and simulations.

II OPERATIONAL BACKGROUND

Operational considerations play an important role in developing the particular problem to be addressed in this research. Special Operations Forces (SOF) have difficult missions to perform and stand to benefit from an automated formation control system, such as proposed. This research is tailored, at least in a generic sense, to SOF operations in terms of aircraft, formations, and maneuvers considered in the study.

2.1 Special Operations Forces Mission Objectives

If one thing can be said concerning a standard SOF mission, it can only be as follows: "There is none." The description cited in Section 1.1 of capabilities required of SOF pilots and their aircraft, lends some idea to missions areas of interest. Although actual mission objectives are not of interest here, their priority is normally critical. Flight tactics are tailored to specific mission objectives and may try to exploit covert flight by using low altitude operations, terrain masking, night, and poor weather tactics.

2.2 Tactics

Tactics used in the execution of these missions are tuned toward achieving the highest probability of success. Tactics of interest for this research involve those for remaining covert throughout several portions of the mission profile. Mission covertness can be increased many fold by appropriate use of tactics. Survivability tactics and covertness include a balance between low level flight for concealment, and altitude

for safety. Low altitude reduces the probability of interception or enemy fire, but it also increases the probability of terrain, vegetation, or obstruction impact. The inverse is also true, increased altitude reduces the probability of hitting the ground, but also increases the probability of being intercepted by enemy defense forces. An optimal flight corridor based on probability of survival, which quantifies this balance, shows an altitude of 100 to 200 feet altitude Above Ground Level (AGL) is the safest altitude for these flight operations (20:17-18).

Another survivability tactic involves a similar trade-off between aircraft separation within a formation. A tight formation of aircraft reduces the land mass overflown by that formation, thereby reducing the number of ground stations that may result in an intercept by the enemy. Several other benefits are enjoyed by close formations versus extended formations. Aircraft can be in visual contact with other formation members depending on visibility conditions, this allows the formation to fly accurately with less electronic emission, which directly reduces the threat of being intercepted.

Close formation flights can also better predict and coordinate terminal phase operations. Since all members of the formation are in closer contact, errors between relative aircraft measurements are reduced. An additional benefit to this reduction in relative errors also allows better use of expensive sensors and navigational equipment. For example, if one aircraft is equipped with a highly accurate, advanced Terrain Referenced Navigation (TRN) system, other aircraft without this equipment which are flying in close formation benefit from the increased accuracy of

that particular navigational system without requiring a similar system on each aircraft.

The other side of this separation distance question is of course the safety impact of flying closer formations. As separation distance is reduced, the chance of aircraft collision increases. During interviews with SOF pilots by Air Force Flight Dynamics Laboratory personnel, one pilot commented, "It's not that we want to fly closer together in poor weather, it's because we have to just to see each other. We would rather fly farther apart and not have to worry about keeping visual contact" (8).

Regardless of the particular formation used, the ability to fly a formation, unrestricted by limitations of systems, visibility, or other matters, would greatly increase the effectiveness of those missions. Formations could then be optimized for effectiveness, and not based on the shortcomings or limitations of systems used to fly those missions.

2.3 Aircraft

Special Operation Forces use a myriad of different aircraft for specific tasks or missions including observation, transport, in-flight refueling, search, rescue, and attack. This collection of aircraft represents various models of C-130 fixed-wing aircraft and H-47, H-53 and H-60 helicopters (21:13). Aircraft considered in this study are the C-130 fixed wing transport and the H-53 helicopter, a transport/search and rescue helicopter.

2.3.1 C-130 Aircraft. Numerous versions of this aircraft are currently used. The Lockheed AC-130H Spectre gunship is a modified C-130

configured with a side-firing gun system, extensive sensor and detection systems, and an air refueling capability (can take on fuel) (16:1). HC-130P/N aircraft are C-130s modified to perform air refueling (off-load fuel) and rescue missions. The HC model is used to refuel helicopters capable of taking on fuel in flight, such as the MH/HH-53 and MH-60 helicopters (17:1). The MC-130E Combat Talon is modified specifically for SOF special operations. It is equipped with the Fulton Surface-To-Air-Recovery system, specialized aerial delivery equipment, secure communication, sophisticated navigation equipment, electronic warfare, and an aerial refueling system (18:1). Each of these models, due to their slightly different configurations and loadings, have different operating characteristics and capabilities.

2.3.2 **H-53 Helicopter**. As in the case of the C-130 aircraft, several different models of the H-53 helicopter are currently in use. Versions of this twin-turbine engine, single rotor, heavy lift helicopter have been used for search, rescue, recovery, space program support, and other special operations in the past. This research concentrates on the MH-53J Pave Low Helicopter developed specifically for Special Operations Forces. The MH-53J is considered the most sophisticated helicopter in the free world due to its many specialized, integrated systems which provide night/all weather, threat penetration capability (19:1).

2.4 Formations

Diamond and trail formations described in Section 1.8 are employed during this research and are both operationally important for this type of mission. A diamond or 'V' formation, as shown in Figure 1, is often used

for cruise portions of a mission (1:34) as it allows good relative visibility between formation aircraft. The trail formation shown in Figure 2 is sometimes used during a turn or threat/terrain clearing, such as flying through a valley or choke-point which is only wide enough for single file formations (1:56). Trail formations are important with regard to covert operations as the minimum amount of landmass is overflown. This translates to a minimum chance for interception by ground forces.

2.5 Maneuvers

Maneuvers used for this study are simplified in terms of how they are accomplished by individual aircraft within the formation. A turn or heading change would be executed differently than as a flat, level maneuver as described in section 1.9.1. Each aircraft would maneuver independently through the turn, maintaining speed to conserve the energy that would be lost in changing velocity to maintain position through the turn. While numerous tactics are used to this end for different aircraft, the formation is typically not maintained through the turn, but regroups after its execution. In one case however, this type of flat turn would be justified. In a covert operation where a minimum altitude was to be maintained throughout the mission, wing aircraft would except a loss in energy in order to maintain the assigned altitude and position.

In the case of a ridge crossing as described in Section 1.9.2, the entire formation would not climb and descend at the same time. A closer profile to the terrain would be flown with each aircraft climbing at the same point in space, not in time. A fighter aircraft would also, for

sharp terrain peaks, add roll to the profile in order to descend faster upon crossing the peak of the terrain obstruction.

III CONTROL THEORETICAL BACKGROUND

Building on operational aspects of the study covered in previous sections, this chapter addresses control or numerical aspects of the research and describes the development of aircraft and formation mathematical models, reference systems, sensor measurements, control strategy and structure, and kinematics. Basic performance is evaluated showing a requirement for additional control.

3.1 Aircraft Plant Models

As stated in Section 1.5, the intent of this research does not include or require exact, non-linear models for individual aircraft used in the study. These aircraft constitute inner loops of the overall formation control system and, as such, low order models representing overall dynamic plant responses are used. These models are verified for accuracy to the extent possible as described later. State space representation, as described in the next section, is used for all models for ease of computer implementation. Development of state space models is described below.

3.1.1 State Space Representation. State space representation is based on first order differential equations which represent the particular plant of interest. State equations of an *n* state system include a set of *n* first order differential equations, where *n* is the number of independent states (6:33). State space equations for a Multiple Input Multiple Output (MIMO) system are shown in equation (1).

$$\dot{\mathbf{x}} = [A]\mathbf{x} + [B]\mathbf{u}$$
$$\mathbf{y} = [C]\mathbf{x} + [D]\mathbf{u} \tag{1}$$

Where:

$\mathbf{x}$ = n by 1 state vector

$\mathbf{u}$ = m dimensional input vector

$\mathbf{y}$ = l dimensional output vector

A = n by n plant coefficient matrix

B = n by m control matrix

C = l by n output matrix

D = l by m feed-forward matrix (6:34).

The D matrix, described above, represents a feed-forward path passing inputs through to the outputs. This matrix is equal to zero for this study to fulfill the assumption of no feed-forward paths or data stream as discussed in the previous chapter.

3.1.2 Plant Control States. To simplify development of plant models for individual aircraft, models used in this research represent aircraft responses outside the individual control surface level. Instead of modelling 'control surface' inputs and 'aircraft' responses, the models developed represent 'flight path' control inputs and responses such as those in an autopilot system. Of interest in this research are internal and overall formation dynamics and the control strategy and structure of the formation control system itself.

Aircraft level control parameters command the flight control system of each wing aircraft to a set point, relative to the lead aircraft. Individual aircraft control parameters are velocity (V), magnetic heading (H), and altitude (A). Reference parameters used to control these states

are longitudinal, lateral, and vertical separation distances the wing aircraft is to maintain from the lead aircraft. These separation distances are represented by rectangular x, y, and z distances of a reference frame further defined in Section 3.2. Each wing aircraft, through its own flight control system, maneuvers to eliminate errors between this target position and its current, real state.

3.1.3 Aircraft/Helicopter Plant Model. As this research does not require exact aircraft models for simulation, first order models are used which duplicate the dynamics involved in transiting from one state to another. Modelling individual aircraft in terms of its flight path responses to control inputs, allows a single model to be used for both fixed wing and rotary wing aircraft, even though they use different control effectors to make similar flight path changes. Models are overdamped to eliminate overshoot at the individual aircraft level and perform precise tracking with delays normal to those particular systems with no steady state error. Basic transfer functions and their state space representations are shown below in equations (2) - (5). Transfer functions and aircraft limitations were developed using information from a number of different sources. Information was obtained from extensive conversations with C-130 and H-53 SOF pilots and other organizations, aircraft DASH 1 manuals, and from flight test data obtained from the Air Force Flight Test Center. The input vector is described in a later section.

$$\frac{V}{V_C} = \frac{G_V}{s + G_V} \tag{2}$$

$$\frac{H}{H_C} = \frac{G_H}{s + G_H} \tag{3}$$

$$\frac{A}{A_C} = \frac{G_A}{s + G_A}$$

$$[\dot{X}] = \begin{bmatrix} -G_V & 0 & 0 \\ 0 & -G_H & 0 \\ 0 & 0 & -G_A \end{bmatrix} [X] + \begin{bmatrix} G_V & 0 & 0 \\ 0 & G_H & 0 \\ 0 & 0 & G_A \end{bmatrix} [u]$$

$$[y] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} [X] \tag{5}$$

where:

V	=	Velocity
H	=	Heading
A	=	Altitude
G_V	=	Velocity channel gain.
G_H	=	Heading channel gain.
G_A	=	Altitude channel gain.

These transfer functions were determined based on their over-damped response characteristics and speed of response, as they represent the speed at which the plant initiates a commanded change. The rate at which the plant reaches the new commanded state must be added to these functions, and is described later in this section. Longitudinal position along the flight path vector is a direct function of forward velocity, which in turn is controlled by flight condition and forward thrust. With a fixed wing aircraft, velocity is a response to flight condition and aircraft parameters such as engine thrust, spool up time, and propeller

pitch. These responses are very fast for a C-130 since they have a constant speed propeller allowing the engine to operate at a constant speed. Thrust is then only a function of propeller pitch regulated by hydraulic pressure. Lateral position is a function of directional control or turn response, while vertical position and spacing is varied by altitude control.

Although helicopters control their flight conditions and flight path differently from a fixed wing aircraft, their overall flight path responses can be modelled similarly. A helicopter such as the H-53 has a faster control response than the C-130 in both lateral and longitudinal axes due to its smaller size. Forward thrust is developed by a series of effector actions for a helicopter. The helicopter must increase the collective pitch of the rotor blades, which creates increased thrust perpendicular to the rotor disk. This thrust increase is then rotated forward by pitching the helicopter down, through cyclic control of the rotor blades, which rotates the thrust vector forward and increases forward velocity. These actions more or less occur simultaneously, resulting in a velocity response which is faster than the C-130. The H-53 also operates at a constant engine speed, varying cyclic and collective blade pitch by hydraulics.

Different models of both C-130 and H-53 aircraft have similar response characteristics, although their limits and capabilities are different. Gains for these individual plant response models are shown in Table 1. A block diagram of the basic, step response model is shown in Figure 8, unit step responses for these system models are shown in

Figure 9. These models are based on the speed of response or onset rates for each axis.

Table 1 Basic Response Model Gains

Aircraft Model	G_V	G_H	G_A
C-130	3	1.5	2
H-53	2	3	3

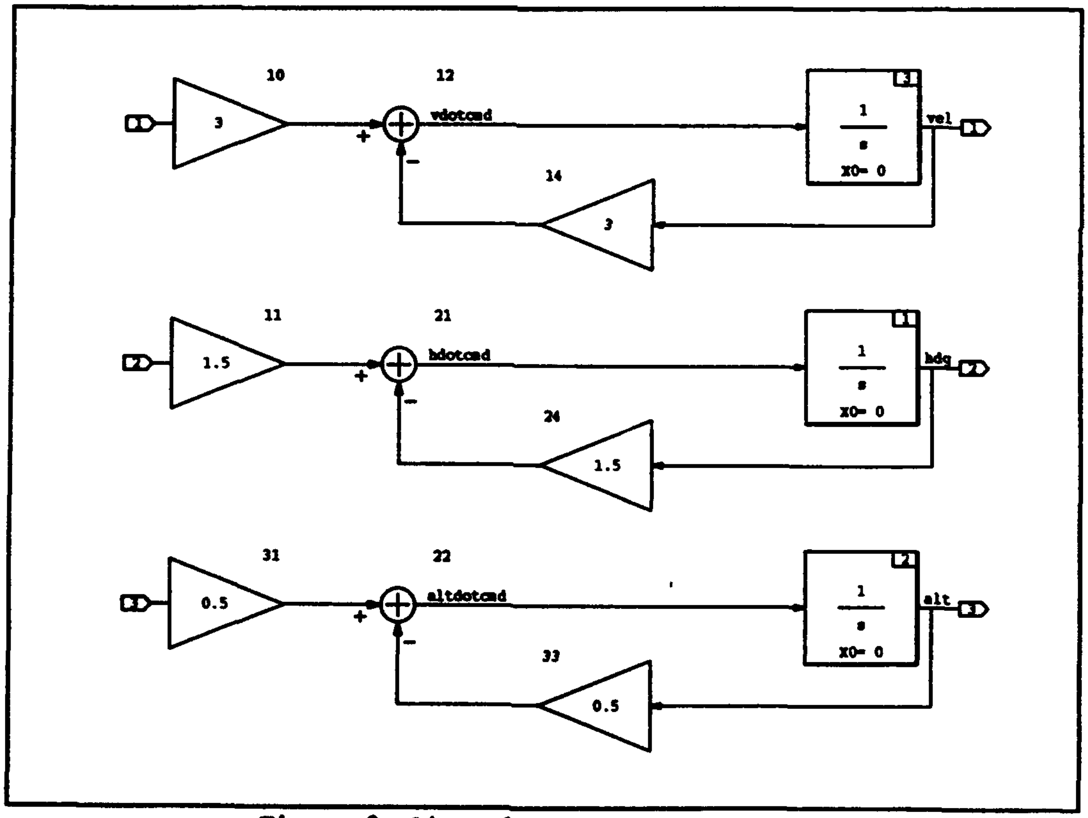

Figure 8 Aircraft Step Response Model

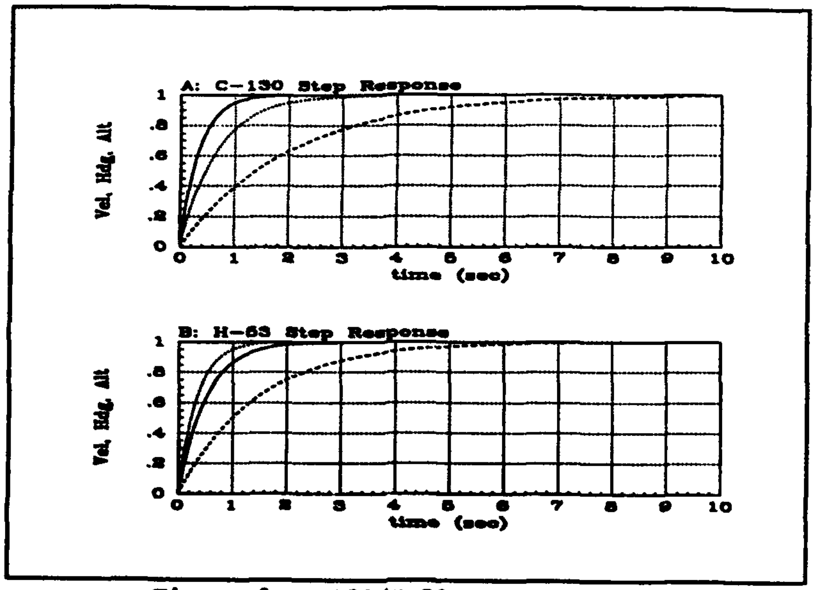

Figure 9 C-130/H-53 Step Response

The simulation models incorporate limiters to more accurately reflect aircraft operating limits and capabilities such as velocity, turn rate, climb/dive rates as well as their onset rates and delays. Values used in these limits are based on actual capabilities or flight restrictions of the aircraft or its systems. Limits were determined through extensive conversations with SOF pilots who fly these aircraft, and flight test data obtained from the Air Force Flight Test Center at Edwards Air Force Base. Helicopter longitudinal axis acceleration and deceleration values were derived using methods of Prouty (15:365-366) which were scaled by weight, power and rotor blade area for the H-53 helicopter. These values are summarized for the C-130 in Table 2, and for the H-53 in Table 3.

As this research is interested in aircraft with slightly different flight characteristics, two models of each aircraft are developed. A less

Table 2 C-130 Aircraft Limitations

Aircraft Model & Parameter	Onset Delay	Onset Rate	Lower Limit	Upper Limit
C-130a				
Velocity	< 1 s	1.5 kt/s^2 2.5 ft/s^2	180 kt 304 ft/s	250 kt 422 ft/s
Heading	~ 1.5 s	1.5 deg/s^2	-3 deg/s	+ 3 deg
Altitude	~ 1 s	-8.4 ft/s^2 to 1.7 ft/s^2	-2500 ft/m -42 ft/s	500 ft/m 8.5 ft/s
C-130b				
Velocity	< 1 s	2.3 kt/s^2 3.9 ft/s^2	180 kt 304 ft/s	250 kt 422 ft/s
Heading	~ 1.5 s	2 deg/s^2	-4.7 deg/s	4.7 deg/s
Altitude	~ 1 s	-8.4 ft/s^2 to 6.6 ft/s^2	-2500 ft/m -42 ft/s	2000 ft/m 33 ft/s

capable model (a) reflects system operating limits encountered during certain flight modes such as terrain following, the second model (b) is based on more capable aircraft structural and power limits. Block diagrams for all four limited C-130 and H-53 models are shown in Figures A-1 through A-4 and located in Appendix A.

Although numerous sources of aircraft transfer functions were uncovered for the C-130, these transfer functions were the result of aerodynamic coefficient analysis and did not include actual closed loop flight control system performance. To verify the models' validity, step response data for the unlimited model transfer functions, and limited versions, were compared with flight test data obtained from the Air Force

Table 3 H-53 Helicopter Limitations

Aircraft Model & Parameter	Onset Delay	Onset Rate	Lower Limit	Upper Limit
H-53a				
Velocity	< 1 s	17.8 kt/s^2 +9 ft/s^2 -9 ft/s^2	80 kt 135 ft/s	120 kt 202 ft/s
Heading	~ 1.5 s	2 deg/s^2	-3 deg/s	+ 3 deg
Altitude	~ 1 s	-14 ft/s^2 to 8.3 ft/s^2	-2500 ft/m -42 ft/s	1500 ft/m 25 ft/s
H-53b				
Velocity	< 1 s	23.7 kt/s^2 11.25 ft/s^2 -9 ft/s^2	80 kt 135 ft/s	120 kt 202 ft/s
Heading	<< 1 s	3 deg/s^2	-4 deg/s	4 deg/s
Altitude	<< 1 s	-8.4 ft/s^2 to 11 ft/s^2	-2500 ft/m -42 ft/s	2000 ft/m 33 ft/s

Flight Test Center at Edwards Air Force Base, and from DASH 1 manuals known to the pilots that fly these aircraft. Data used for this verification consisted of time response plots produced during C-130 H model systems evaluation by Dryden Flight Research Facility at Edwards Air Force Base, California. Velocity and acceleration limits were determined through pilot interviews and MC-130 Dash 1 Flight Manual.

Plots of this data provided turn, climb and descent rates, and time responses for maneuvers initiated and controlled by the autopilot system.

These results show complete, actual closed loop system responses of the aircraft to a control input, which was required to verify models developed for this research.

Again, it must be emphasized, exact modelling of the aircraft used for this research is not required. The proof of concept of this type of formation control system allows low order models to be used. A follow-on topic for research is the insertion of high order models for the specific aircraft of interest, but that is not intended here.

In comparing operating limits and capabilities of different C-130 and H53 models, note the differences in operating limits such as turn, climb, and descent rate capability and forward acceleration. Such differences are of major concern for a formation control system capable of controlling a formation of mixed aircraft. These differences could allow one aircraft to outmaneuver another within the formation, resulting in either an aircraft that loses the formation, or worse, a collision within the formation. For this reason, formation level control must account for these differences and limit maneuvering to prevent aircraft from ever being directed to maneuver outside of their individual limitations.

3.1.4 Formation Control System. As described in section 1.5, a control system for formations of like or dissimilar aircraft must be robust in providing safe, positive control, as well as flexibility to allow aircraft within the formation to change positions, or changes in the formation configuration itself, as required. Numerous additional functions are assumed when compared to a standard flight control system. The system must only command maneuvers which are within the flight

restrictions and capabilities of all aircraft in the formation. The system must also operate in consideration of the current state of each aircraft within the formation.

3.2 Formation Reference System

Formation control requires a common reference system upon which all formation aircraft can relate reference and control parameters against, to relate their positions and maneuvers to the lead aircraft. Three basic reference systems could be used for formation flight as described by Ballantyne in an early Army study of helicopter formation flight (1:38). These are the inertial frame, lead ship reference, and own-ship frame.

The inertial system is a rectangular system based on a stationary origin with latitude, longitude, and altitude as its axes. This system is used for navigation and is best used over long distances. The inertial system requires instruments for accurate data, but can be extremely accurate as a common reference for multiple players. Basic navigational data is normally described in terms of an inertial frame (1:38).

A lead-ship reference system is a spherical system originating at the lead aircraft's position. This system describes a follower's position relative to the lead aircraft in terms of separation range, relative bearing, and relative altitude (1:38).

For this research, an own-ship reference system is used based on a vehicle carried vertical frame as defined by Etkin (7:108), with its x axis coincident with the vehicle's direction of flight, the y axis perpendicular and extending laterally to the right, and the z axis toward

the earth. This system is normally used by individual pilots in follower aircraft to relate their own position to the lead aircraft (1:41), whether using instruments or flying visually. As shown in Figure 10 and Figure 11, this spherical own-ship system matches the measurements provided by a wing aircraft's on-board sensor, of lead aircraft position relative to that wing aircraft.

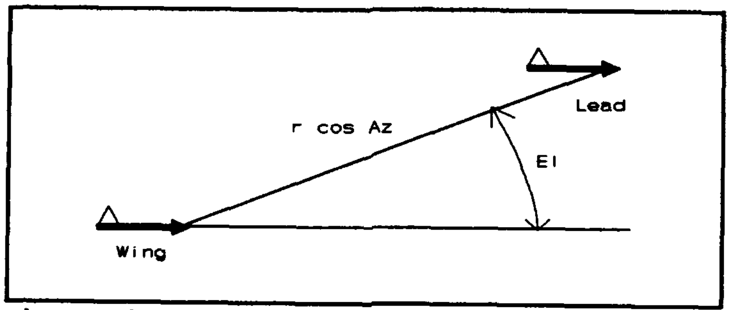

Figure 10 Own-ship Reference System - Side View

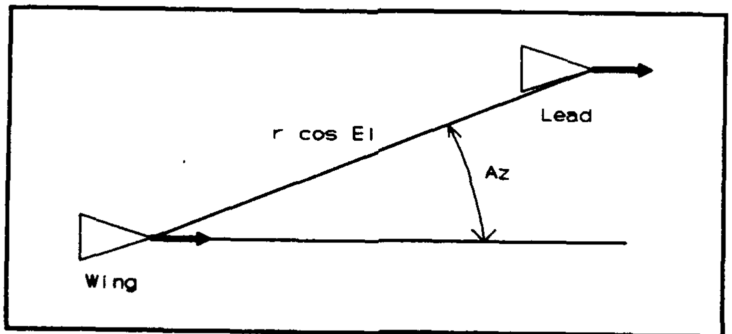

Figure 11 Own-ship Reference System - Top View

Note from the two figures that relative position is completely defined by three parameters of separation range, elevation angle, and azimuth angle. Only elevation angle (El) is required in the vertical plane, azimuth angle (Az) determines horizontal position, and range (r) is used in both planes as shown in the figures. These parameters are easily

transformed into rectangular longitudinal, lateral, and vertical separation distances (dx, dy, and dz) as illustrated in Figure 12 and Figure 13. This rectangular set is used for this research.

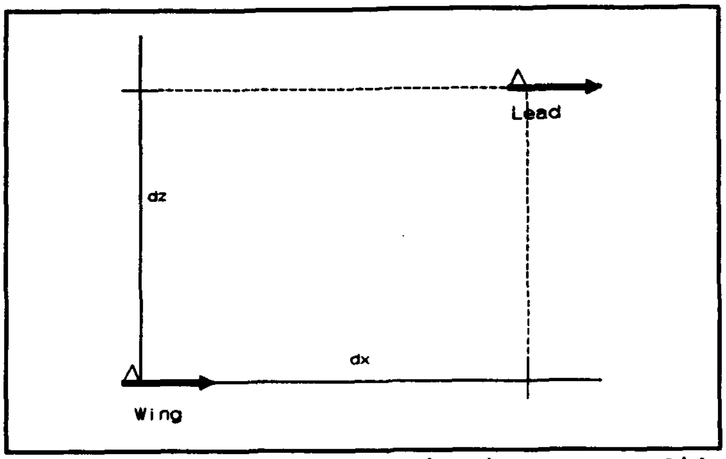

Figure 12 Wing Aircraft Navigation Frame - Side View

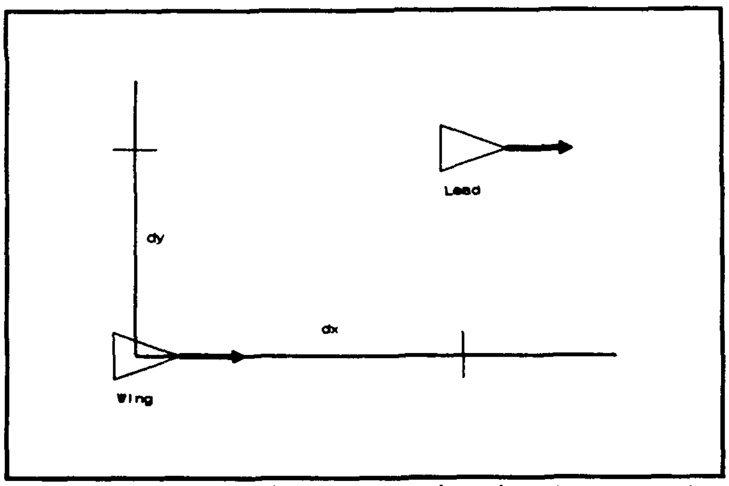

Figure 13 Wing Aircraft Navigation Frame - Top View

3.3 Wing Aircraft Sensor Measurements

As stated in section 1.5, a sensor resides on each wing aircraft for the purpose of this study. The sensor operates in the wing aircraft's

reference frame deriving relative lead aircraft position in terms of range, and azimuth and elevation angles. These measurements are again transformed into dx, dy, and dz for this study.

3.4 Formation Control Strategy

Controlling strategy for individual aircraft within a formation considers many things which differ from a standard control set for that individual aircraft. Two major differences are noted. First, in addition to controlling overall maneuvering of the formation, a formation control system must insure individual aircraft remain separated during required maneuvering. Secondly, formation maneuvering must be limited so as not to exceed the capabilities of any formation member.

For this research, a two tiered control strategy is defined as shown in Figure 14. Formation level guidance is provided in earth axes to all formation aircraft. These inputs include formation velocity, magnetic

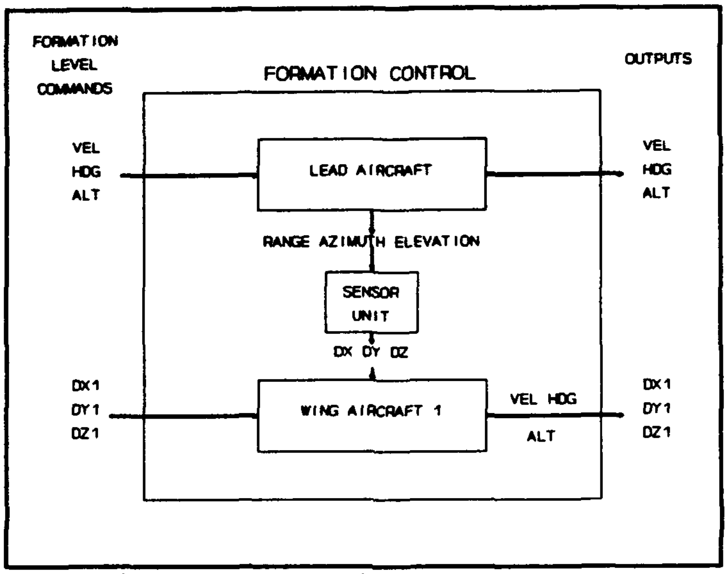

Figure 14 Formation Control System

heading, and altitude, as well as the particular formation to be flown. The formation itself is defined by a set of commanded separation distances (dx, dy, and dz). Each wing aircraft is controlled by a different set based on his position number in the formation.

Individual aircraft level control is different for each formation aircraft. The lead aircraft uses commanded formation velocity, heading, and altitude for aircraft guidance, while wing aircraft maneuver to maintain their respective commanded separation distances from the lead aircraft. Wing aircraft on-board sensor measurements track lead aircraft position relative to the wing aircraft.

Formation control level inputs and individual aircraft feedback terms are summarized in equations (6) and (7) respectively.

$$\underline{FC} \triangleq \begin{bmatrix} V_L \\ H_L \\ A_L \\ W_{1C} \\ W_{2C} \\ \bullet \\ \bullet \\ \bullet \end{bmatrix} \tag{6}$$

where:

$\underline{FC}$	=	Overall formation control vector
V_L	=	Formation (lead) velocity command
H_L	=	Formation (lead) heading command
A_L	=	Formation (lead) altitude command
W_{1C}	=	Commanded separation vector for wing # 1
W_{2C}	=	Commanded separation vector for wing # 2

and

$$\underline{W_{1C}} \triangleq \begin{bmatrix} dx_{W1C} \\ dy_{W1C} \\ dz_{W1C} \end{bmatrix} \tag{7}$$

where:

W_{1C}	=	Wing aircraft # 1 control input vector
dx_{W1C}	=	Commanded longitudinal separation
dy_{W1C}	=	Commanded lateral separation distance
dz_{W1C}	=	Commanded vertical separation distance

The measurement vector for these separations has the same form without the C subscripts. Wing aircraft measurements (dx, dy, and dz), formation reference separation distances (dx_{WC}, dy_{WC}, and dz_{WC}), as shown

in equation (6), are differenced to create control inputs for each wing aircraft for tracking the lead aircraft's actual position by the sensor inputs. These constitute feedback terms within the system for tracking. Wing aircraft maneuver to eliminate errors in these distances. Wing aircraft are to maintain the reference separation from the lead aircraft, based on that wing's position number. For example, wing aircraft in position two would have a different parameter set than wing position one. This data is received by all formation members which allows for position changes of individual aircraft. The data set is changed for different formations, as when converting from trail to diamond formation.

3.5 Formation Simulation Model Structure

This section describes the development of formation models for computer simulation. These mathematical representations perform two functions. First, they represent individual formation aircraft in terms of their control input responses. Secondly, they model cross couplings of relative aircraft spacings due to the kinematics of individual aircraft maneuvering within the formation.

Formation models consist of several levels as shown earlier in Figure 14. Individual aircraft plant models were discussed in Section 3.1. These constituent plant models are treated as separate sub-blocks in the overall formation model shown in Figure 14. Treated as such, different aircraft are easily substituted into the overall formation model. Linking these aircraft sub-blocks into the formation are couplings representing inputs, responses, kinematics, and outputs of individual formation aircraft.

External formation inputs, as described in equation (6), direct overall formation flight, as well as the particular formation to be flown. The lead aircraft is controlled by the commanded formation velocity, heading, and altitude. Wing aircraft are provided separation distances from the formation control vector based on the wing aircraft rectangular reference frame as described in Section 3.2. Wing aircraft track these x, y, and z distances by comparing them with actual separation distances measured by their on board sensors. Wing aircraft guidance is thus provided in order to null these tracking errors.

In keeping with covert operations as assumed for this research, formation inputs are not continuous. These inputs are assumed to come as a single data burst, to be flown until further data is received. In the case of real-time data from on-board sensors as in terrain obstructions, these signals would still be assumed discontinuous in keeping with covert operations. If terrain following radar was the sensor used for terrain following, minimal emissions would be used, providing a stream of data at a certain rate as a series of step inputs. As such, changes in these inputs are seen as step inputs of varying magnitudes. External formation outputs describe the operation of individual aircraft in the formation, and separation distances of aircraft within the formation.

Creating lead aircraft relative position measurements, as seen by wing aircraft sensors introduces complexities into the system during simulation. Actual measurements represent the difference between the wing and lead aircraft's maneuvering referenced to the wing aircraft's reference frame. These measurements are based on kinematics describing

the maneuvers of individual aircraft as developed in the following section.

3.6 Formation Kinematics

Basic kinematics describe relationships between individual aircraft maneuvering and relative spacings within the formation. Relative motions between aircraft are functions of individual aircraft maneuvering. For instance, if the lead aircraft initiates a turn, this maneuver will be seen as a lateral velocity relative to each wing aircraft. Since individual formation aircraft are inherently decoupled from other aircraft in terms of flight control, relative position states must be created based on wing aircraft on-board sensor measurements as shown earlier in Figure 10 through Figure 13. These are used for simulation purposes in place of sensor measurements. Internal formation couplings are developed in terms of these dx, dy, and dz distances for this study for ease of development. The x, y, and z channels are developed separately and integrated into complete formation models. Individual channel (x, y, and z) control laws are developed in the following sections.

3.6.1 Longitudinal (X) Channel. This channel involves separation distance of a particular wing aircraft, from the lead aircraft, in that wing aircraft's x direction as defined in 3.2. The wing aircraft controls this separation by varying longitudinal velocity. External, formation level inputs command a nominal formation velocity and target separation distance (dx_c) along that wing aircraft's x axis. The lead aircraft tracks the formation nominal velocity while wing aircraft maintain separation distance. As the separation distance increases or decreases from its

commanded value, the wing aircraft's velocity is varied above or below the commanded nominal value. An increase in dx, as when the lead is accelerating away from the wing aircraft, causes an increase in the wing aircraft's velocity in an attempt to null out errors in separation distance. A decrease in separation distance, (wing and lead aircraft are closing), causes a decrease in the wing's velocity.

The wing aircraft's velocity also requires control during a turn. If the lead aircraft maneuvers a right turn, it will eventually cross the flight path of a wing aircraft following to the right. For this reason, the wing aircraft on the inside of a flat turn must decelerate during a turn and then accelerate to the original velocity after the turn is completed. A wing aircraft on the outside of the turn must accelerate during the turn, then decelerate. Range measurements must provide this information to the wing aircraft based on the lead aircraft's maneuvering.

It is assumed that both aircraft are initially at some nominal separation distance. Velocity difference between the lead aircraft's velocity component along the wing aircraft's x axis and wing aircraft velocity (V_W) are used to compute changes in this separation distance. This relative velocity, when integrated, provides a perturbation in dx from the initial separation distance. This perturbation distance is subsequently used as a control input to the velocity of the wing aircraft as the velocity and separation are of the same order of magnitude. Longitudinal control law development for this channel is shown in equations (8) through (11).

$$\frac{V_L}{V_{LC}} = \frac{V_W}{V_{WC}} = \frac{3}{s + 3} \tag{8}$$

$$V_{WC} = V_L + dx_W - dx_{WC} \tag{9}$$

$$dx_W = \frac{1}{s} \left[V_L \cos(H_W - H_L) - V_W \right] \tag{10}$$

$$V_W = V_L + \int [V_L \cos(H_W - H_L) - V_W] \, dt - dx_C \tag{11}$$

Beginning with the transfer functions for lead and wing aircraft velocity responses, a simple development leads to the final velocity control law for this x channel. Note the cross coupling inherent in the x channel from the lateral channel, seen as heading angle (H). This term is required so only that lead aircraft's velocity component along the wing aircraft's longitudinal axis is used for measurement.

3.6.2 Lateral (Y) Channel. This channel controls lateral separation distance of wing aircraft from the lead aircraft. As in the x channel, target lateral separation distance (dy_C) is provided as a formation level input to wing aircraft. They in turn employ lateral maneuvers (coordinated turns), to maintain their target lateral position. This allows wing aircraft to follow the lead aircraft through heading changes, or change formation spacing based on new formation level

commanded separation distance. This channel is inherently cross coupled with the longitudinal axis.

Again, an initial, nominal heading angle and separation distance is assumed for both lead and wing aircraft. The lead aircraft tracks the nominal formation input while wing aircraft heading angle is controlled to maintain commanded separation distance from the lead aircraft regardless of lead aircraft maneuvering. In order to generate an input, for simulation, to the wing aircraft's on-board sensor, the lateral velocity component of the lead aircraft along the y axis of the wing aircraft is developed. This lateral velocity component is derived from the lead aircraft's velocity and the difference in heading angles between the lead and wing aircraft.

This relative lateral velocity is integrated, producing a lateral displacement from the wing aircraft's target relative position as done for the x channel. This perturbation is used as an input to control wing aircraft heading angle. This is shown in equations (12) through (15).

$$\frac{H_L}{H_{LC}} = \frac{H_W}{H_{WC}} = \frac{1.5}{s + 1.5} \qquad (12)$$

$$H_{WC} = H_L + \frac{\Delta y}{dx} \qquad (13)$$

$$\Delta dy = \int [V_L \sin(H_W - H_L)]\, dt \tag{14}$$

$$H_{WC} = H_L + \frac{dy_C - \frac{1}{s}[V_L \sin(H_W - H_L)]}{dx} \tag{15}$$

The control input angle to the wing aircraft's heading is determined as the ratio of the lateral displacement error (Δdy) to the x axis separation distance dx. This is required so that, at greater longitudinal separation distances, lateral separation errors seen by the wing aircraft's sensor require less maneuvering by the wing aircraft to follow the same lateral displacement. For example, a fifty foot lateral displacement at a one thousand foot longitudinal separation, requires less wing aircraft heading correction than the same fifty foot lateral displacement with a longitudinal separation of only two hundred feet. Two formation level inputs effect this channel - formation heading and target lateral separation distance.

3.6.3 Vertical (Z) Channel. The third channel required for complete control of individual aircraft is the vertical or z axis. Again, this separation distance (dz) represents the separation of the wing aircraft from the lead aircraft, referenced to the z axis of the wing aircraft's rectangular reference frame. Target vertical or z axis separation and nominal formation altitude are provided as formation level inputs to each aircraft. Wing aircraft controls relative lead aircraft

spacing through altitude control, climbing or descending to maintain proper spacing.

This axis is decoupled from the other (x and y) axes. An initial altitude and vertical spacing is assumed as initial conditions. Perturbations from the given target vertical separation are used as controlling inputs, directing individual wing aircraft to climb or descend, as required, to eliminate vertical position errors. Formation inputs that affect this channel are a change in the lead aircraft's altitude, and a change in target vertical separation. Control law development for this channel is shown in equations (16) and (17). This control law is simpler than those of the x and y axes since the control and reference parameters are of the same factor, not a rate such as in the x and y axes. Both reference and control states are distances in feet.

$$\frac{A_L}{A_{LC}} = \frac{A_W}{A_{WC}} = \frac{2}{s+2} \tag{16}$$

$$A_{WC} = A_L + dz_C \tag{17}$$

3.6.4 __Formation Feedbacks and Couplings__. Rigorous development of wing aircraft sensor measurements based on lead aircraft maneuvering are described in this section. Both lead and wing aircraft dynamics must be related to an inertial frame since both maneuver simultaneously. Actual wing aircraft sensor measurements are computed from differences between lead and wing aircraft flight conditions as described in the previous

section. These measurements form the controlling feedbacks used as inputs to wing aircraft. Since each of the measurements is based on the difference between lead and wing aircraft maneuvering relative to the same inertial reference frame, inertial effects are eliminated, and only the maneuvering parameters remain. In other words, only maneuvering data for the lead and wing aircraft are required to compute relative measurements. This must be accomplished for each channel or axis. These calculations form the control feedbacks which control wing aircraft maneuvering.

3.7 2 Ship Formation Model Simulation

The basic two ship model consists of two aircraft connected by feedbacks and couplings based on kinematics and sensor measurements. Model structure is the same, regardless of what aircraft models are used for simulation. Two versions of the basic two-ship model are developed. Formation 1 (F1) consists of two similar aircraft, formation 2 (F2) consists of two aircraft with differing operational capabilities. These are C-130 aircraft models (a and b) as developed in Section 3.1.3. The basic 2 ship formation model (F2) is shown in Figure 15, full size diagrams of both F1 and F2 are shown in Figures A-5 and A-18 respectively.

Six different inputs are required to fully evaluate two ship model operation. Table 4 summarizes initial conditions and input magnitudes used to evaluate the system. The longitudinal or x channel responds to changes in commanded lead aircraft velocity and x axis separation; the lateral or y channel responds to commanded formation heading and lateral separation; the vertical or z channel responds to commanded formation altitude and z axis separation. Ten outputs are of interest to a two ship

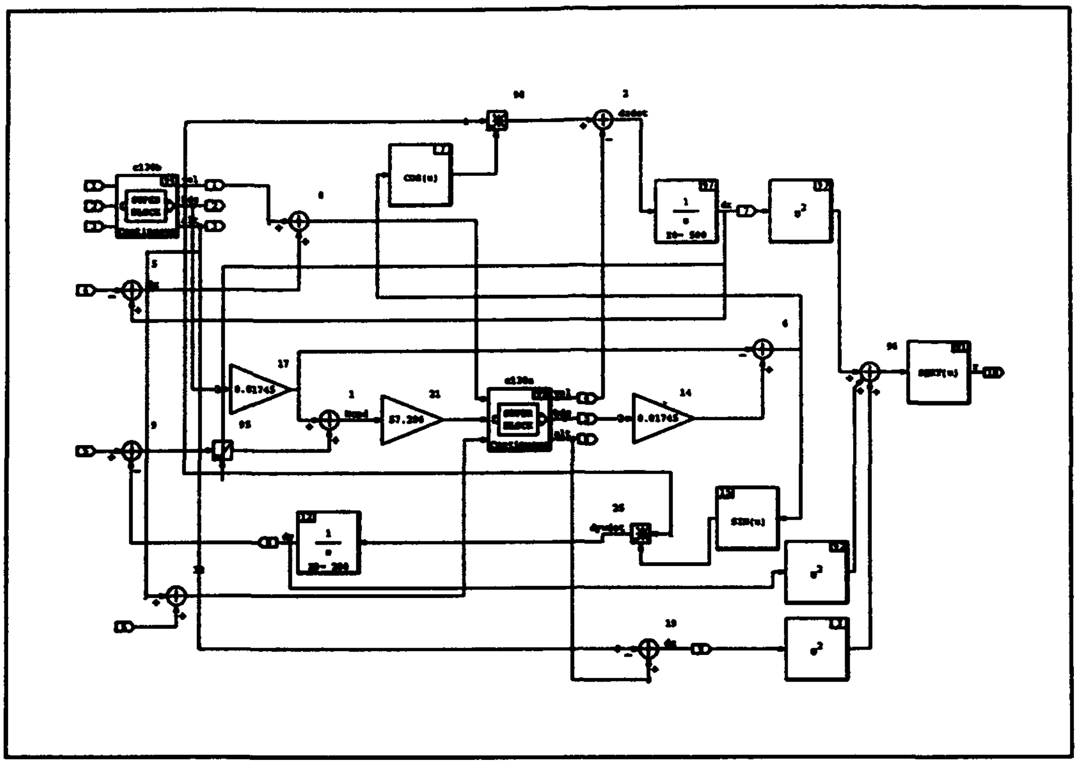

Figure 15 Basic 2 Ship Formation Model

formation model; three flight path parameters (V, H, and A), for the lead and wing aircraft, three separation distances (dx, dy, and dz), and the actual range (r) they represent. Table 5 correlates these inputs, their responses, and locations of their respective plots contained in Appendix A. Pertinent responses are analyzed in subsequent sections.

3.8 <u>3 Ship Formation Simulation Model</u>

A three ship model, although more complex than the two ship model, is merely two separate two ship models with a common lead aircraft. As in the two-ship model, two versions of this model are developed. Formation 3 (F3) has all similar aircraft, formation 4 (F4) contains one dissimilar wing aircraft. For a three-ship formation, the same inputs are used as in

Table 4 C-130 2-Ship Formation Initial Conditions and Input Magnitudes

Parameter	Initial Condition	Input Magnitude
V_L	230 kt 388 ft/sec	250 kt 422 ft/sec
H_L	30 deg	35 deg
A_L	500 ft	550 ft
dx	500 ft	550 ft
dy	200 ft	250 ft
dz	0 ft	50 ft

the two-ship formation with the addition of a second set of separation distances defining the target position of the second wing aircraft. The number of outputs, although, have more than doubled. Flight path parameters are required for all three aircraft, but now, not only must the positioning of the wing aircraft relative to the lead aircraft be controlled, but the positions of each wing aircraft relative to other wing aircraft must also be controlled. Full page block diagrams for each of these formations are shown in Figures A-31 and Figure A-50. Inputs used to exercise the formation, and the locations of their appropriate response plots are included in Appendix A and summarized in Table 6 and Table 7 respectively.

The beauty of this control strategy now becomes clear. Regardless of how many aircraft are in formation, if their positions are referenced to a single lead aircraft, their control becomes a simple task. Each wing aircraft has a prescribed set of position target parameters dx, dy, and dz different from those of other wing aircraft.

Table 5 2 Ship Formation Input & Response Summary

Formation	(F1) 2 Similar a/c		(F2) 2 Dissimilar a/c	
Input Parameter	Outputs of Interest	Response Plots	Outputs of Interest	Response Plots
Longitudinal Channel				
V_L	V_L, V_W dx, r	A-6 A-7	V_L, V_W dx, r	A-19 A-20
dx	V_L, V_W dx, r	A-8 A-9	V_L, V_W dx, r	A-21 A-22
Lateral Channel				
H_L	H_L, H_W dy, r	A-10 A-11	H_L, H_W dy, r	A-23 A-24
dy	H_L, H_W dy, r	A-12 A-13	H_L, H_W dy, r	A-25 A-26
Vertical Channel				
A_L	A_L, A_W dz, r	A-14 A-15	A_L, A_W dz, r	A-27 A-28
dz	A_L, A_W dz, r	A-16 A-17	A_L, A_W dz, r	A-29 A-30

where:

A = altitude
H = heading
V = velocity
L = lead aircraft
W = wing aircraft
dx = longitudinal separation
dy = lateral separation
dz = vertical separation
r = absolute range from lead aircraft

Aircraft separation is insured by assignning different separation distance commands to each wing aircraft. Responsibility of maintaining separation lies with each wing aircraft. By all wing aircraft maintaining position relative to a common lead, instabilities and second order effects are eliminated. Any number of aircraft could be flown this way. Wing

Table 6 C-130 3-Ship Formation Initial Conditions and Input Magnitudes

Parameter	Initial Condition	Input Magnitude
V_L	230 kt 388 ft/sec	250 kt 422 ft/sec
H_L	30 deg	35 deg
A_L	500 ft	550 ft
Diamond Formation		
dx_{W1}	500 ft	550 ft
dy_{W1}	200 ft	250 ft
dz_{W1}	0 ft	50 ft
dx_{W2}	500 ft	450 ft
dy_{W2}	-200 ft	-150 ft
dz_{W2}	0 ft	-50 ft

aircraft of one formation, could be lead for another sub formation with the addition of feed-forward paths from the lead to sub-lead aircraft.

3.9 <u>Measures of Merit</u>

Numerous means are available to evaluate the operation of a formation control system as defined for this research. For the simplest case, does the system do what it is supposed to do? Does the system track as required and eliminate all tracking errors? This means a system of appropriate order so as to track inputs over time with zero steady state error. This approach only describes whether or not the system works, it does not provide information as to 'how well' the system works, or if it makes sense and is reasonable as a real system.

Table 7 3 Ship Formation Input & Response Summary

Formation	F3=L(b), W1(b), W2(b)		F4=L(b),W1(b),W2(a)	
Input Parameter	Outputs of Interest	Response Plots	Outputs of Interest	Response Plots
Longitudinal Axis				
V_L	V(L,W1,W2) dx(1,2,W) r(1,2,W)	A-32 A-33 A-34	V(L,W1,W2) dx(1,2,W) r(1,2,W)	A-51 A-52 A-53
dx1,dx2	V(L,W1,W2) dx(1,2,W) r(1,2,W)	A-35 A-36 A-37	V(L,W1,W2) dx(1,2,W) r(1,2,W)	A-54 A-55 A-56
Lateral Axis				
H_L	H(L,W1,W2) dy(1,2,W) r(1,2,W)	A-38 A-39 A-40	H(L,W1,W2) dy(1,2,W) r(1,2,W)	A-57 A-58 A-59
dy1,dy2	H(L,W1,W2) dy(1,2,W) r(1,2,W)	A-41 A-42 A-43	H(L,W1,W2) dy(1,2,W) r(1,2,W)	A-60 A-61 A-62
Vertical Axis				
A_L	A(L,W1,W2) dz(1,2,W) r(1,2,W)	A-44 A-45 A-46	A(L,W1,W2) dz(1,2,W) r(1,2,W)	A-63 A-64 A-65
dz1,dz2	A(L,W1,W2) dz(1,2,W) r(1,2,W)	A-47 A-48 A-49	A(L,W1,W2) dz(1,2,W) r(1,2,W)	A-66 A-67 A-68

where:

L = lead aircraft
W1/2 = wing position number
a/b = simulation model a or b

Additional information is required to determine if the system can control individual formation aircraft within their own flight limitations and capabilities. If the formation includes two wing aircraft, these aircraft must never be commanded to fly in such a way that a collision can occur between them, or with them and the lead aircraft! A means to

monitor this possibility is therefore required. A simple determination of separation range is computed during operation for this research. Separation distances dx, dy, and dz, and the range they represent between lead and wing aircraft, and between individual wing aircraft, are outputs of the system and constitute one simple measure of merit.

Numerous other schemes can be used, depending on what is a priority of system operation. This can depend on mission phase or objective and may change during a particular mission. For instance, a long cruise portion of a mission may have a relaxed priority on maintaining precise separation distances, and a higher priority on providing a smooth ride for occupants. A terminal phase or ingress to attack may have a tighter requirement on maintaining precise spacings between aircraft, but may still include limitations on maneuvering due to weapons stores or sensor limitations.

This limitation on maneuvering leads to the next step in this research. As stated earlier, formation maneuvering must be limited to the weakest aircraft in the formation. The lead aircraft cannot command a three G turn and expect a wing aircraft which is limited to two G's to follow. The same analogy follows for each of the formation's maneuvering axes. Velocity accelerations, turn, climb, and dive rates must be limited to those of the weakest aircraft in the formation for that particular axis. In following the control strategy developed for this formation control system, this requires that the lead aircraft is never commanded to maneuver in a way that cannot be followed by all wing aircraft.

This research uses a proportional plus integral (PI) controller designed to serve this purpose. The system controller limits formation level command inputs to those that all wing aircraft can follow.

3.10 Analysis Of Basic Formation System Performance

The basic performance of the formation models developed in previous sections are evaluated in this section. Formation 4 performance is used for evaluation, as it illustrates performance of both like and dissimilar formation aircraft. Operation as defined thus far is open loop operation as there are no feedback paths from formation outputs into the system level or lead aircraft inputs. Responses to the six inputs described in the previous section are shown in the following figures and briefly analyzed below. Tables 6 and 7 should be referred to for initial conditions and input magnitudes for these plots. Plots contain three parameters whose names are shown on the y axis of each plot. The first parameter coincides to the solid line on the plot, the second is the dotted line, and the third is shown by the dashed line. This is so for each plot in this study.

In previous sections, individual aircraft control models and higher level formation models are developed for computer simulation. These models represent not only aircraft response models to input commands at the aircraft level, but also lead aircraft dynamics relative to the wing aircraft reference frame as described in Section 3.2. The basic operation of the formation control system is somewhat intuitive. A commanded input to the lead aircraft results in a maneuver initiated by that aircraft. As this maneuver causes a motion relative to wing aircraft, wing aircraft

command their own maneuvers in order to follow the lead while maintaining commanded relative position.

In formations of similar aircraft, (formations 1 and 3 of this research), wing aircraft maneuvering based solely on relative lead aircraft motions poses no problem as wing aircraft can always match lead aircraft maneuvering after some inherent time lag. However, in the case of dissimilar aircraft (formations 2 and 4), there is the chance that one aircraft may outmaneuver another, less capable aircraft. If the less capable aircraft is in the lead position, it may maneuver at will since the more maneuverable wing aircraft is capable of matching the lead's maneuvering. If, however, the lead aircraft is more capable than a wing aircraft, the lead aircraft could outmaneuver and lose a wing aircraft, or, worse, cause a collision among formation aircraft.

Operation of the longitudinal axis is effected by inputs of lead or formation velocity (V_L) and longitudinal separation (dx). Responses for these two inputs are shown in Figures 16 and 17 respectively.

Note in Figure 16A, lead aircraft velocity responds in a first order fashion to reach the new commanded velocity. Wing 1, (a similar aircraft) reaches the target velocity with some overshoot to eliminate changes in dx due to lag in acceleration. Wing 2 however, (a dissimilar aircraft) cannot accelerate as rapidly as the lead and wing 1 aircraft, resulting in an increasing dz throughout the lead's acceleration. Wing 2 continues its acceleration until he overshoots the target dx as shown in Figure 16B, and only then begins to decelerate, which in turn causes it to oscillate about

the target position until finally reaching it after about 18 seconds for a 25 ft/sec commanded acceleration.

A commanded increase in dx, shown in Figure 17 A and B, shows the velocity and dx response for a 50 foot increase in dx for wing 1, and a 50 foot reduction in dx for wing 2. While the lead aircraft maintains its nominal formation velocity, the wing aircraft accelerate or decelerate at their capability limits as required into their new positions. The overshoot is a bit more pronounced in this case compared to that in Figure 16.

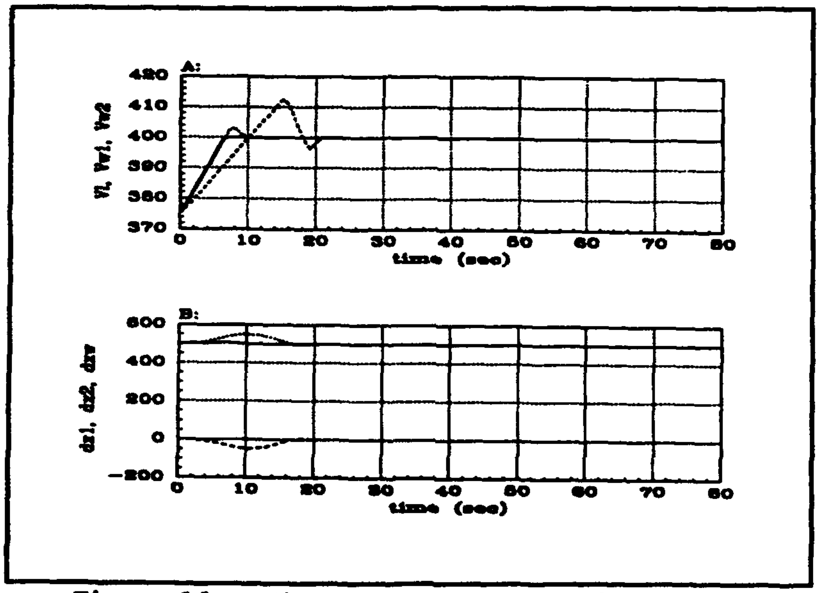

Figure 16 X Channel Response to V-lead Input

Responses for y or lateral axis inputs are effected by inputs in formation heading (H) or lateral separation (dy). Figures 18 and 19 illustrate these responses. Figure 18A shows a very smooth and rapid

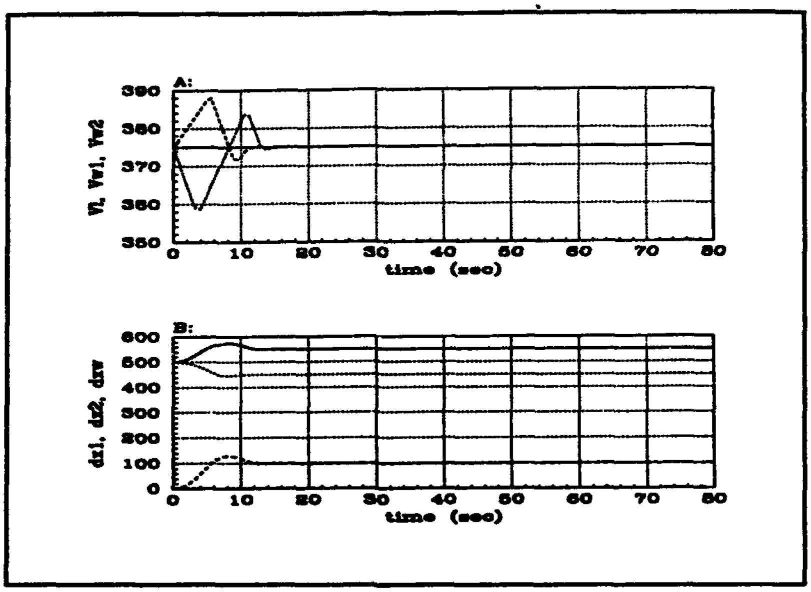

Figure 17 X Channel Response to dxwl, dxw2 Input

response to a change in heading command. Again, a first order response for the lead aircraft and a small overshoot for each of the wing aircraft to eliminate changes in lateral separation due to lag in the wing aircraft responses. A commanded change in lateral separation shows, again, a smooth response, increasing heading approximately 3.5 degrees for a short duration to achieve a 50 foot change in separation. Wing 1 and 2 were commanded a change in the same direction (to the right) relative to the lead aircraft.

Vertical channel operation shows a first order response for both formation altitude (A) and vertical separation (dz) commands as illustrated in Figures 20 and 21 respectively. The first order nature of the responses is due to the transfer functions of the system as shown in Equation (17). Each aircraft, lead or wing, when given either an altitude or a separation command, sees the change in input as the same. The

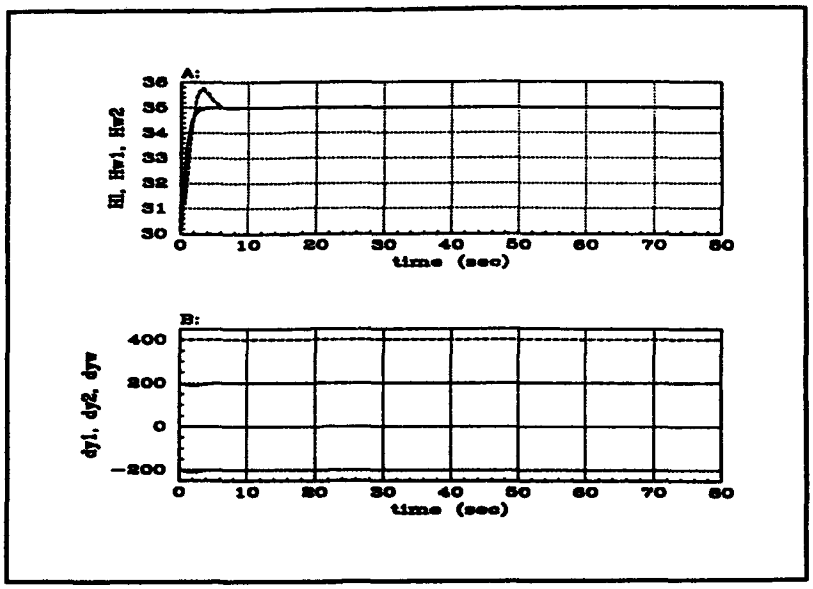

Figure 18 Y Channel Response to H-lead Input

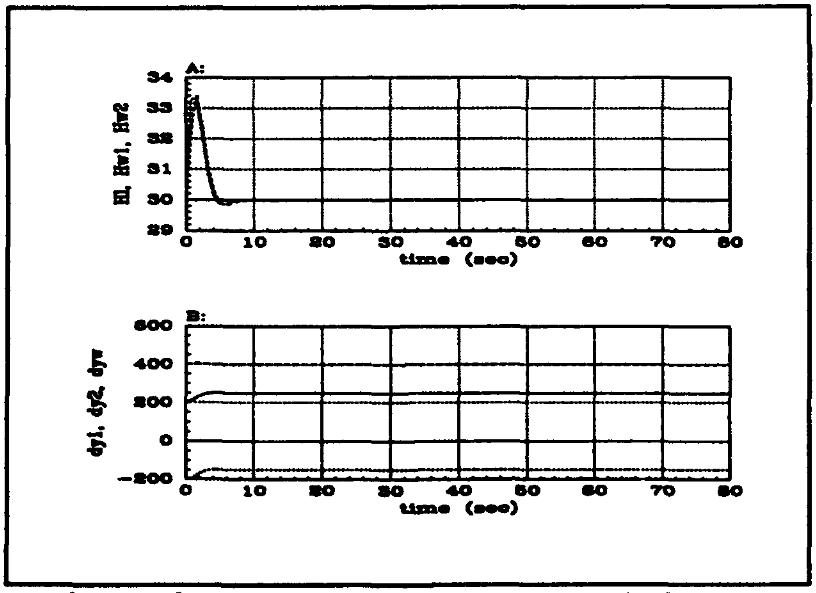

Figure 19 Y Channel Response to dywl,dyw2 Input

responses clearly reflect this operation as Figures 20A and 21A show essentially the same response, but to a 50 foot increase in altitude, or a positive or negative 50 foot change in dz.

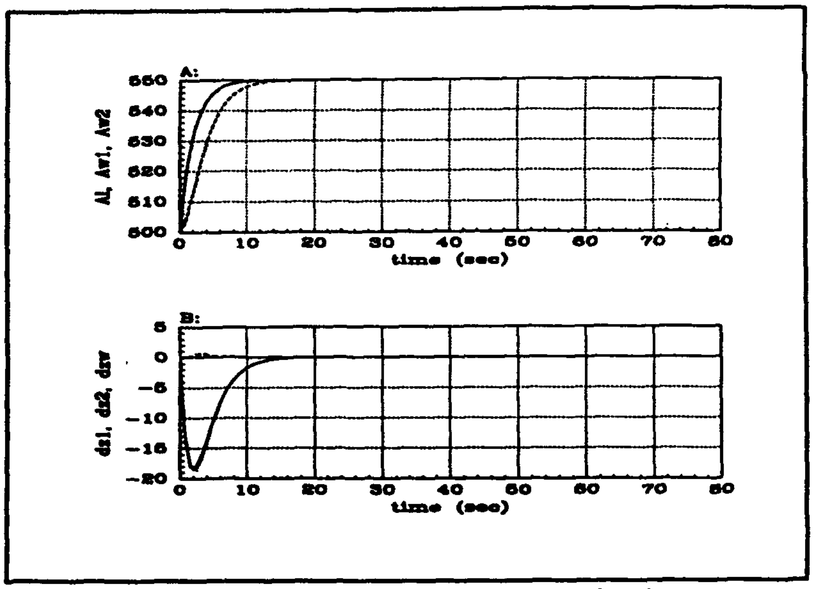

Figure 20 Z Channel Response to A-lead Input

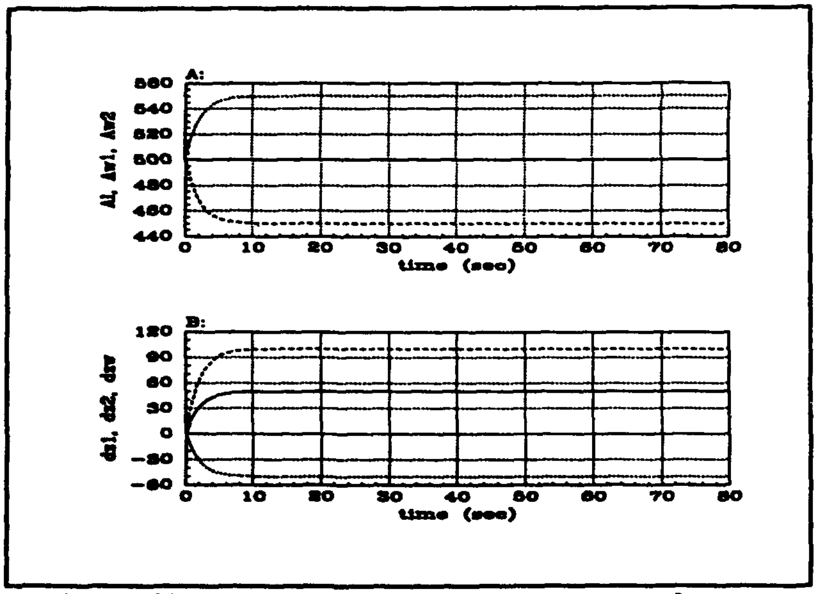

Figure 21 Z Channel Response to dzw1, dzw2 Input

In the basic performance considered thus far, formation inputs have consisted of small magnitude step commands. In the case of a more capable aircraft in the lead position, less capable wing aircraft are capable of

reasonably maintaining formation through small magnitude command inputs. However, large magnitude inputs cannot be followed while reasonably maintaining the formation, as illustrated below.

In a flat turn, a wing aircraft capable of out-turning another, can actually cross the flight path of the less maneuverable wing aircraft while following a lead aircraft turn in that wing aircraft's direction. To illustrate this problem, a diamond formation is composed of a C-130b aircraft model as lead and wing #1, positioned 500 feet behind and 200 feet to the right of the lead aircraft at the same altitude (dx=500, dy=200 and dz=0). A less capable C-130a aircraft model is used as wing #2 and positioned on the opposite side and adjacent to wing #1 (dx=500, dy=-200 and dz=0). The formation is commanded a 30 degree left heading change which turns the formation into the less capable wing #2 aircraft. As the lead and wing #1 aircraft are capable of a three degree per second turn rate, and wing #2 is only capable of a two degree per second rate, in time, the flight path of wing #1 aircraft crosses that of wing #2 so that they collide. Aircraft headings, lateral and absolute separation responses are shown in the following figures.

Note in Figure 22A, that the heading of all aircraft, in time, achieve the commanded input. However, as seen in Figure 22B, the lateral separation of the less capable wing #2 strays from the original position of -200 feet, to a position of +200 feet which is where wing #1 is positioned. Figure 22C shows the absolute ranges between aircraft; note the range between the two wing aircraft (rw) is seen to go from 400 feet to zero where their flight paths meet.

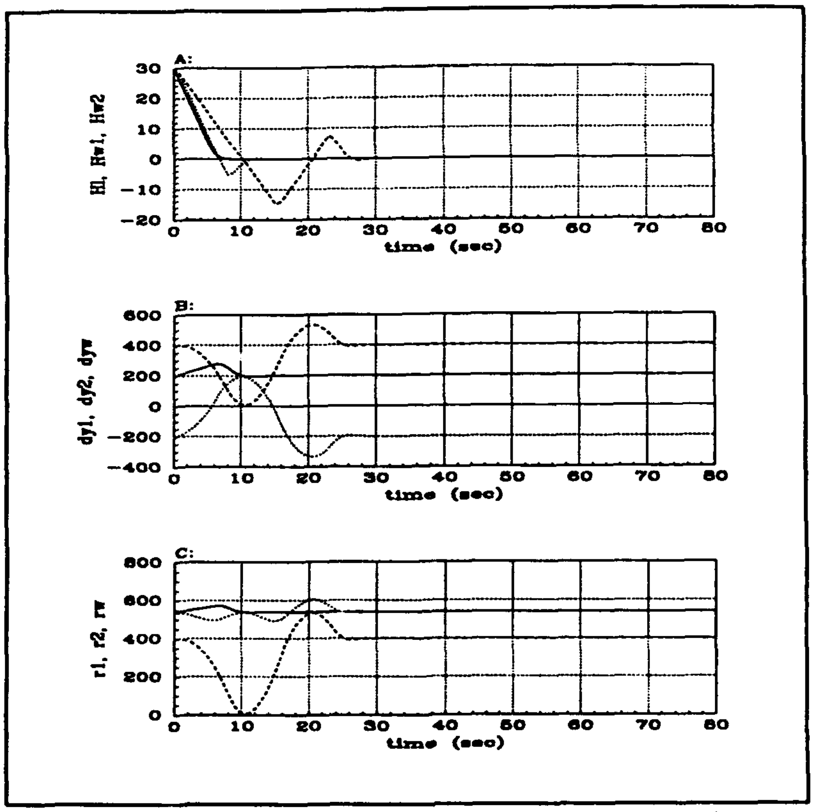

Figure 22 Uncontrolled Response To Large H-lead Input

A similar problem involves the x axis and is based on an assumed range limitation of the wing aircraft's sensor used to track the lead aircraft. This range is arbitrarily set for the purposes of this study, any range, with an appropriate velocity command, can be used to show the same results. If the lead aircraft is capable of accelerating faster than the wing aircraft, such an acceleration could cause the lead aircraft to pull away from the wing aircraft to the point where it exceeds the wing aircraft sensor's range limit. To illustrate this problem using the formation described above, assume a sensor range limitation of 1000 feet. The system is initially slowed from its nominal velocity, then commanded an increase as shown in Figure 23A. This acceleration from 310 ft/sec

(184 kts) to 400 ft/sec (237 kts) results in a maximum longitudinal separation (dx) of approximately 1100 feet as shown in Figure 23B respectively.

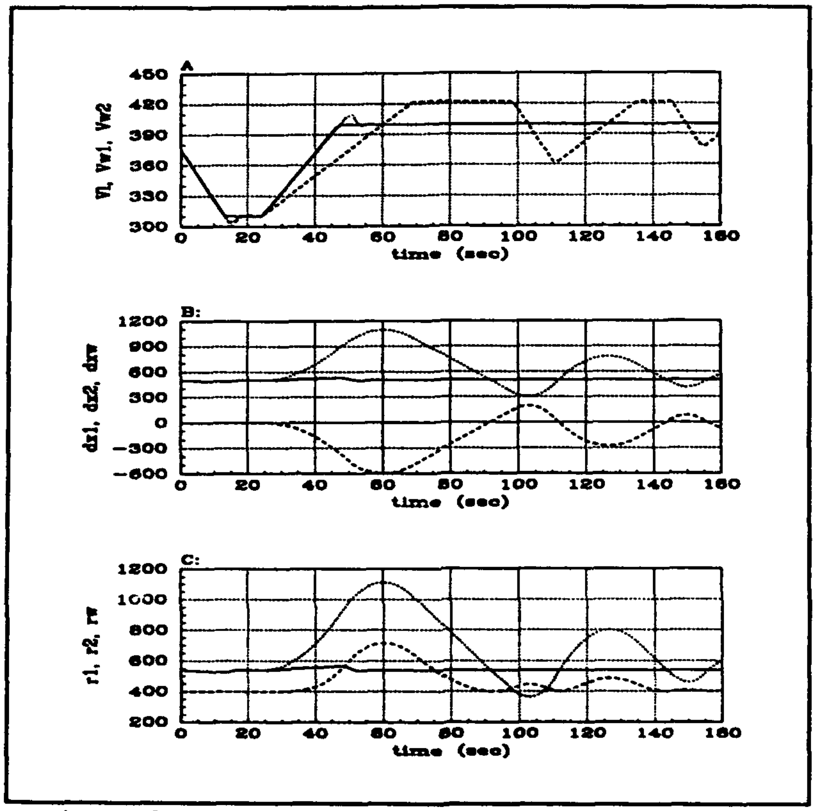

Figure 23 Uncontrolled Response To Large V Input

Absolute range of this wing aircraft (r2) further exceeds that separation as shown in Figure 23C. These figures also show the time required for the less capable wing #2 aircraft to 'catch' up to the lead aircraft during this acceleration exceeds the simulation time of 160 seconds.

As illustrated by these two examples, additional control must be levied at times on the lead aircraft to prevent it from outmaneuvering the

less capable aircraft in the formation, and to allow less capable aircraft to better maintain control over separation distances during maneuvering.

A further requirement for additional control is illustrated by the velocity and separation response to a commanded, longitudinal separation increase/decrease (100 foot increase used here) input shown in Figure 24A

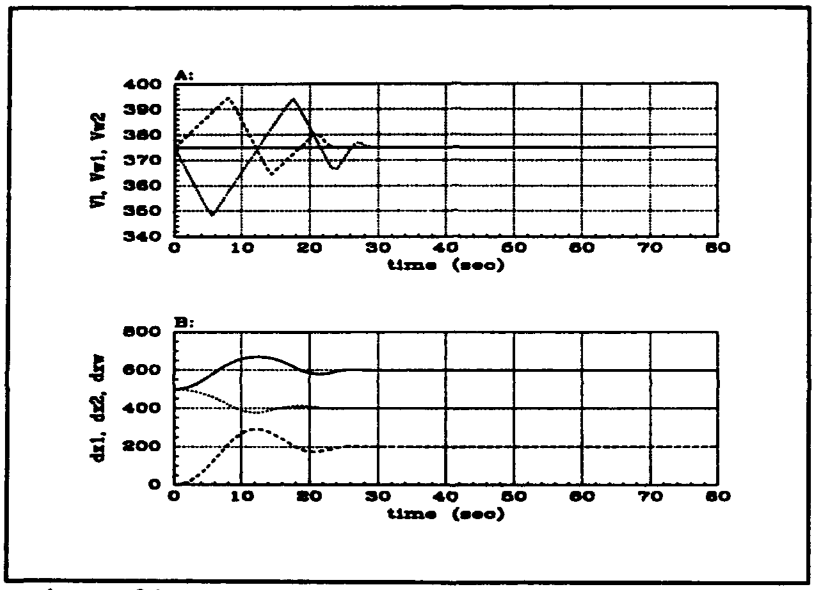

Figure 24 Uncontrolled X Axis Response to dx Input

and B respectively. It is seen that when an increase in longitudinal separation (dx) is commanded, the wing aircraft accelerate/decelerate at their maximum rates to effect the change in dx. These aircraft continue to speed up/slow down until the new target separation is reached. At this time, they begin to resume their initial commanded velocity, oscillating into that goal separation over time. This is not acceptable operation and additional control is required to eliminate this oscillation.

into that goal separation over time. This is not acceptable operation and additional control is required to eliminate this oscillation.

With the additional control requirements outlined here, an overall formation system controller is designed in the following chapter.

IV FORMATION CONTROLLER DESIGN

Previous sections describe basic tracking and control requirements for this research, modelled individual aircraft plants and formations, and developed overall system structure as described in Section 3.4. In evaluating basic performance of these formations, it is shown that additional control is required on lead aircraft maneuvering. This additional control is especially important for large magnitude formation maneuvers, commanded through a lead aircraft more capable than at least one wing aircraft. This example is used to illustrate that requirement in the previous chapter.

This chapter describes the development of basic controller design goals and procedures, and subsequently describes the design of a controller to meet these additional control requirements.

4.1 Design Requirements and Goals

Outer loop control for this study commands flight of the formation itself, and accounts for differing flight characteristics or limitations of different formation aircraft. Performance of basic formation models developed in the previous chapter illustrate the need for additional lead aircraft control. The goal of this design section is to develop a system controller to insure that the lead aircraft is never commanded in such a way as to outmaneuver a less capable wing aircraft, in any axis. An additional goal is to improve the performance of the system by reducing

the overshoot of a less capable wing aircraft as it acts to 'catch up' with a maneuvering lead aircraft.

An example of this case is illustrated by a commanded lead aircraft velocity increase shown in Figure 24 of the previous chapter. As the lead aircraft is capable of accelerating at a higher rate than the wing aircraft, longitudinal separation increases throughout the maneuver. Once the lead aircraft reaches the new commanded velocity, the wing aircraft continues to accelerate in order to eliminate the increase in separation. Once this separation is again at the commanded magnitude, the wing aircraft slows down, and oscillates back into the correct position.

In this particular problem, that of maneuvering formation control, longitudinal and lateral axis separation distances are inherently more important than the vertical separation. Vertical separation is normally small, as formations are not typically stacked for the type of mission addressed here. Therefore, additional control is added only to the longitudinal (x), and lateral (y) axes.

4.2 Multivariable Control Design Method

Numerous multivariable design techniques are available in the literature. For this research, a proportional plus integral (PI) controller is used to provide additional control for each axis where needed. In formation flight, individual aircraft separation is inherently coupled to the maneuvering of those aircraft through basic kinematics. The objective of this controller design, is to decouple the effects of individual aircraft control and maneuvering on those separation distances within the formation.

Professor Brian Porter of the University of Salford, England has shown in his *singular perturbation methods in the design of tracking systems incorporating high-gain or fast-sampling error-actuated controllers* (References 5, 14), that by judicious selection of gains used in the proportional and integral paths, effects of inherently coupled states within the plants are effectively decoupled or at least minimized. Barfield's thesis (Reference 2), contains a summary of Porter's method of gain selection for the interested reader. The design of the proportional plus integral controller is described in the follcwing sections.

4.3 Design Process

A PI controller, uses the error between the system input and output, summed with that input, and passed through proportional and integral paths, to drive the error to zero. This operation uses two components of the error, its magnitude and its integral. A large input is added by the controller to the system when either the magnitude or integral of that error is large. As the error returns to zero, so does the additional system input added by the controller. Key to this controller operation are gains used in the proportional and integral paths of the feedback controller. As shown by Porter, the goal is to achieve decoupling of control and reference states through these judicious gain selections.

The goal of this research is to control aircraft maneuvering while minimizing effects on formation spacings. The formation, through the lead aircraft, cannot be commanded to maneuver beyond the capabilities of the least maneuverable aircraft in the formation. The net effect of this added control is to limit lead aircraft maneuvering, by attenuating the

inputs, so as not to exceed maneuvering limitations of the least maneuverable aircraft in the formation. A negative effect of limiting lead aircraft capabilities is to reduce the maneuverability of the formation as a whole. This trade-off however, between formation maneuverability and stability is imperative for maintaining formation through all but the smallest maneuvers. The optimum solution eliminates formation maneuvers exceeding the capabilities of any formation aircraft allowing the formation to be maintained, while not appreciably affecting formation response times.

The initial step in this design is to determine what states require additional control or decoupling in the longitudinal and lateral axes. Once determined, attention turns to what signal(s) are to be used, and how, to control formation or lead aircraft inputs. In the formation models developed for this research, the states requiring additional control are directly coupled. Forward velocity of lead and wing aircraft directly effects longitudinal separation, while aircraft headings effect lateral separation.

Error signals are available in both the longitudinal and lateral axes in the simulation models developed for this study. These signals (dxdot and dydot) represent relative longitudinal and lateral velocities between lead and wing aircraft which relate to changing separation distances in these two reference axes. These signals are nominally zero and allow tracking of wing aircraft separation distances, unless a formation change is commanded.

This research assumes that there is no continuous communication between formation members other than lead aircraft relative positions measured from wing aircraft on-board sensors, which form the basis of the entire formation control system. However, the assumption is also made that formation aircraft are capable of exchanging positions within the formation. This implies that the lead aircraft is also supported by a similar on-board sensor, capable of tracking the relative motions of wing aircraft. Signals used for this controller (feed-back), are based on these lead aircraft sensor measurements of wing aircraft position relative to the lead aircraft.

4.4 PI Controller Implementation

Reference 6 provides a description of PI controller design. For this study, the controller is applied to longitudinal (x), and lateral (y) axes for reasons stated in the previous section. Full state outputs are available in both of these axes, therefore none require to be created or reconstructed, (Porter defines a method to accomplish reconstruction of any missing states). The implementation becomes a task of feeding output relative velocities (dxdot and dydot), through proportional and integral paths, to be summed with input formation command signals and fed into the lead aircraft as controlled velocity and heading commands. In this light, the controller is actually controlling the feedbacks, which then affect system inputs. The result therefore, is that of controlling the inputs to the lead aircraft.

Feedback controller outputs are summed with system, or formation level, inputs and fed into the formation itself through the lead aircraft.

These new input commands differ from the original inputs. They are attenuated by wing aircraft performance relative to the lead aircraft. A less capable wing aircraft causes a larger difference between lead and wing maneuvering. This attenuates the lead aircraft's inputs until the wing aircraft is capable of maintaining relative position. Modified input equations are shown in equations (18) and (19). Figure 25 shows a block diagram of the X and Y axis PI controller used for this research.

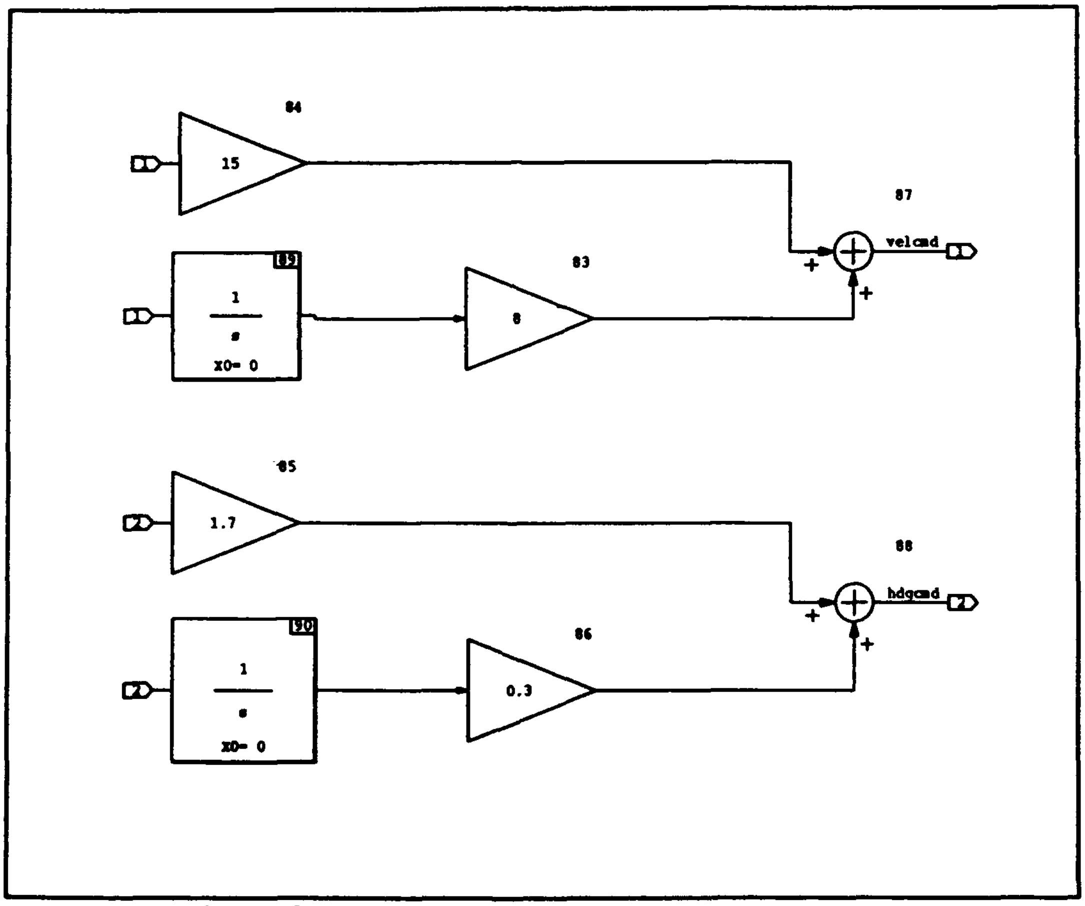

Figure 25 Basic PI Controller (X and Y Channel)

$$V_{Lcc} = V_{Lc} + \dot{dx}\,(G_{Px} + \frac{G_{Ix}}{s}) \tag{18}$$

$$H_{Lcc} = H_{Lc} + \dot{dy}\,(G_{Py} + \frac{G_{Iy}}{s}) \tag{19}$$

Where:

V_{Lcc}	=	Lead aircraft controlled velocity command
H_{Lcc}	=	Lead aircraft controlled heading command
$G_{Px/y}$	=	Proportional path gain (x/y axis)
$G_{Ix/y}$	=	Integral path gain (x/y axis)

Additional consideration must be given to this controller operation. The controller itself is to attenuate lead aircraft input commands only when wing aircraft maneuvering capabilities are exceeded. The signals (dxdot and dydot), nominally zero, take on a non-zero value when wing aircraft motion differs from that of the lead aircraft. This occurs in two cases for both x and y axes: when the lead aircraft accelerates longitudinally or laterally, and when wing aircraft maneuver to assume new commanded formation spacings. This is clearly shown by inspection of the basic formation performance simulations of Chapter III.

If the controller is implemented using only the error signals dxdot and dydot, lead aircraft control inputs are attenuated in both cases based on the relative transient velocities during the maneuvers. However, when wing aircraft maneuver into a new position, the lead aircraft is to remain at its commanded nominal flight condition, and the controller should not effect that steady state input. Therefore, the controller is active only when the lead aircraft is maneuvering into a new commanded nominal formation flight condition. Simulation of this is accomplished through

logic which enables or activates the feedback paths only when lead aircraft longitudinal or lateral accelerations are commanded, and not when a formation configuration change is commanded.

To implement this logic for simulation, a magnitude comparison is made of lead aircraft commanded and actual velocity and heading for their respective axes. If the absolute value of the difference is greater than some arbitrary magnitude, 0.1 is used here, the output of the feedback controller is multiplied by a unity gain prior to being summed with the system input velocity. If the magnitude is less than 0.1, it is multiplied by a gain of zero. In this manner, the feedback controller output is active only when the lead aircraft is accelerating longitudinally or laterally. This determination would be designed into an operational system, the logic used here is strictly for simulation of that operation. The block diagram included later in Figure 28 shows the implementation of the PI controller model and logic for this design.

Another difference between this simulation and an operational system is that feedback paths in this simulation relate only one wing aircraft to the lead aircraft. An operational system would be required to monitor all formation wing aircraft. Lead aircraft maneuvering would be attenuated, based on the operation of the least maneuverable of those wing aircraft. For this study, only the least capable of the wing aircraft is monitored for simulation purposes, however the results are the same. Once the controller and logic are inserted, the gains used in the proportional and integral paths must be optimized for x and y axis control.

4.5 Formation System Controller Gain Selection

This section addresses the selection of gains for the proportional and integral paths for both longitudinal (x) and lateral (y) axes controllers. A trade-off exists between eliminating commanded maneuvers exceeding capabilities of any formation aircraft, and maximizing maneuverability of the formation as a whole. As the lead aircraft's control inputs are attenuated by errors between the lead and a less capable wing aircraft's maneuvering, the time required for the lead aircraft to execute a particular formation maneuver is increased.

Numerous optimization schemes can be used for this selection. As described in Section 3.8, optimization criteria can change within different portions of a single mission. Criteria such as G loadings, formation spacings, and how tight or loose these spacings are held can all be used for this evaluation. For this research, an arbitrary measure of merit is used in determining an acceptable response as the goal is the process, not the actual optimization of the system for a particular goal. Maneuvering responses are optimized such that aircraft maneuvering capabilities are not exceeded, therefore formation spacings are maintained, and the time required to execute a particular maneuver is not increased beyond those of the least maneuverable aircraft within the formation, in executing the maneuver.

In selecting final gain combinations for both longitudinal and lateral axes, a number of combinations were evaluated. A simple matrix approach was used to select gain combinations for evaluation of each channel. The first nine combination are identical for both channels.

From the results of these nine combinations, longitudinal and lateral channel combinations were independently refined in search of an optimum response. X and y channel gain combinations and their responses are shown in Table 8 and Table 9 respectively. From these, a best choice is selected for final control design. Figure 25, shown earlier, reflects the final gain selections. To illustrate improvements, formation responses to the large magnitude heading and velocity commanded inputs (examples from previous chapter) are shown in Figure 26 and Figure 27 respectively.

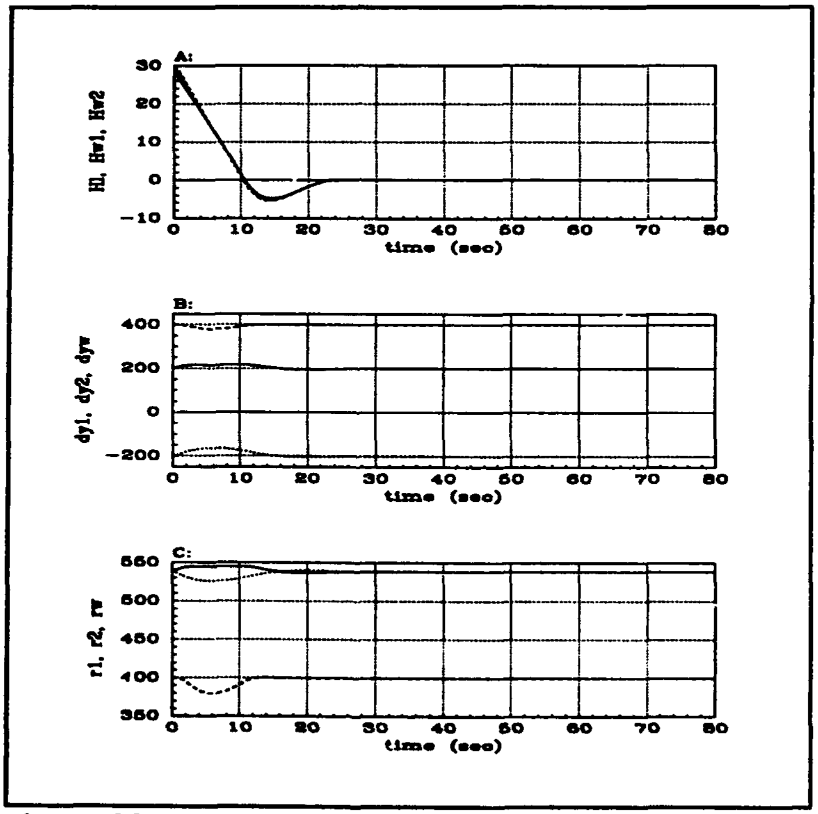

Figure 26 Controlled Responses To Large H-lead Inputs

Note the improvements when these responses are compared with those of Figures 22 and 23 from the previous section showing the uncontrolled

Table 8 Longitudinal Controller Gain Combinations

Longitudinal (velocity) Axis						
#	Gpx	Gix	C/D	Ts (sec)	Vw max (ft/sec)	▲ dx max-ft
1	.5	.5	D	38.4	403	110
2	.5	1	D	38	400	60
3	.5	2	D	38	400	30
4	1	.5	D	41.6	405	105
5	1	1	D	37	401	55
6	1	2	D	36	400	30
7	2	.5	D	44	410	100
8	2	1	D	41	403	60
9	2	2	D	37	400	30
10	.5	10	D	44	400	5
11	10	.5	C	63	420	75
12	10	10	C	41	400	5
13	10	15	C	41	400	< 5
14	15	10	C	39	400	5
15	15	15	C	43	400	< 5

Where:

#	=	combination reference number
Gpx	=	proportional path gain
Gix	=	integral path gain
C/D	=	continuous/discontinuous response
Ts	=	approximate settling time (2 %)
Vw max	=	maximum wing aircraft velocity
▲ dx	=	change in separation distance

responses. For the heading change shown in Figures 22 and 26, the time to reach commanded formation spacings is actually reduced by approximately 6 seconds, from 27 to 21 as shown in Figures 22A and 26A. With the exception of the overshoot, this performance reaches the C-130(a) model limit of 3 deg/sec turn rate. Maximum overshoot for this aircraft is

Table 9 Lateral Controller Gain Combinations

Lateral (heading) Axis						
#	Gpy	Giy	C/D	Ts (sec)	Hw max (deg)	▲ dy max-ft
1	.5	.5	D	16	0	25
2	.5	1	D	30	0	15
3	.5	2	D	> 40	0	10
4	1	.5	~C	13	0	20
5	1	1	~C	30	0	15
6	1	2	D	> 40	0	12
7	2	.5	C	11.5	1	17
8	2	1	C	23	0	20
9	2	2	C	> 40	0	10
10	.5	10	D	> 40	0	~0
11	10	.5	C	16	1	75
12	10	10	C	> 40	0	5
13	10	.1	C	15	2	< 5
14	15	1	C	16	.5	5
15	15	1	C	20	.5	< 5

Where:

#	=	combination reference number
Gpy	=	proportional path gain
Giy	=	integral path gain
C/D	=	continuous/discontinuous response
Ts	=	approximate settling time (2 %)
Hw max	=	maximum wing aircraft heading
▲ dy	=	change in lateral separation distance

reduced from 15 degrees to 5 degrees. Lateral spacing deviations, shown in Figures 22B and 26B, are reduced from 400 feet to less than 50 feet. The absolute range which originally went from 540 feet to zero for the wing aircraft in Figure 22C, is reduced to a deviation of approximately 20 feet as shown in Figure 26C.

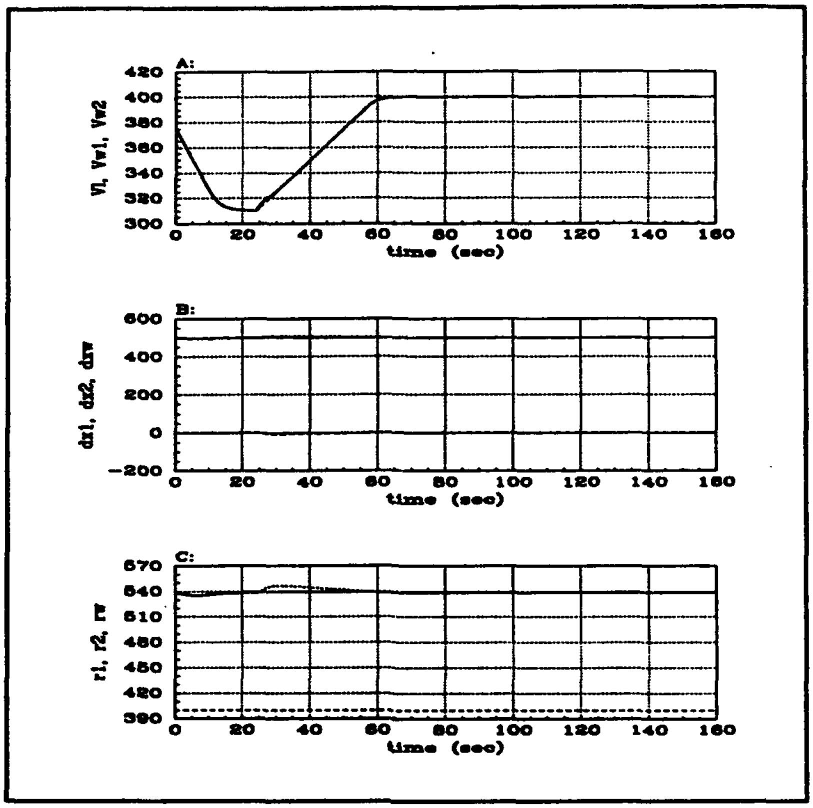

Figure 27 Controlled Responses To Large V-lead Inputs

In the case of a large longitudinal acceleration as shown in Figures 23 and 27, the improvements are just as profound. The uncontrolled maneuver, which is initiated at simulation time of 24 seconds on the plots, hasn't returned to the original formation even at the end of the simulation time of 160 seconds as seen in Figure 23A. Figure 27A shows the maneuver takes approximately 36 seconds. Again, this 90 ft/sec total acceleration is reached at the maximum limit of the less capable aircraft in the formation which is limited to 2.5 ft/sec^2. Figures 23B and 27B show the maximum deviation in longitudinal separation is reduced from over 1100 feet to less than 10 feet. Figures 23C and 27C show the absolute range shows equal reduction in deviation.

4.6 Additional Control Required For Wing Aircraft Velocity

As shown in Chapter III, wing aircraft velocity control, with only a distance measurement for a control input, requires additional control. As illustrated in Figure 24A and B in the previous chapter, when a formation command is provided which increases or decreases longitudinal separation distance (dx), the wing aircraft respectively decreases or increases its velocity to execute the change. While the lead aircraft remains at the nominal formation velocity as shown in the response plots, wing aircraft accelerate or decelerate at full capability to reach the new target separation distance. The wing aircraft's velocity remains high until it passes the target dx and is commanded to reduce velocity.

This strategy, one of only using the separation distance error for control input, causes a higher velocity to be maintained by the wing aircraft completely through the target point. This causes an overshoot until the wing aircraft can slow down, subsequently oscillating back and forth through the new target position until it finally settles into the correct position. With large separation distances, this is not a problem, but it could spell disaster in a tight formation.

This problem is not alleviated by the insertion of the PI controller described in the previous section, since that controller is only active when the lead aircraft has been commanded an acceleration. In the initial formation model, only the relative separation error from the commanded distance is summed with the lead aircraft's velocity to control the wing aircraft's velocity. As velocity is a rate of the distance, this works, however, an additional signal is required. Intuitively, what is needed is

the rate at which this relative distance error is increasing or decreasing. As the error approaches zero, the target wing position, the velocity commanded for the wing aircraft must approach that of the lead aircraft. The new control law for commanded wing aircraft velocity is therefore as shown in equation (20).

$$V_{WC} = V_L + dx - dx_C + \dot{dx} \qquad (20)$$

where

V_{WC}	=	commanded wing aircraft velocity
V_L	=	lead aircraft velocity
dx	=	x axis separation distance
dx_C	=	commanded x axis separation distance

Operation of this additional feedback is such that as the target separation distance is approached, additional velocity being commanded to the wing aircraft will gradually attenuate to zero, thus matching that of the lead aircraft. This controller implementation is included in the complete system block diagram shown in Figure 28 and its effect on system responses to dx command inputs can be seen in Figure 29. Note Figure 29A shows an acceleration/deceleration to achieve the new separation distance. As the target point is reached, velocity commands are reduced in anticipation of reaching the goal separation. This reduces both the time to reach the position and the overshoot of that goal position.

The system controller designed in this chapter, is shown to greatly improve the performance of the overall system and eliminate problems that called for additional control at the formation system level. Basic

formation system performance, as accomplished in Chapter III, will be repeated and evaluated on the controlled formation system in the next chapter.

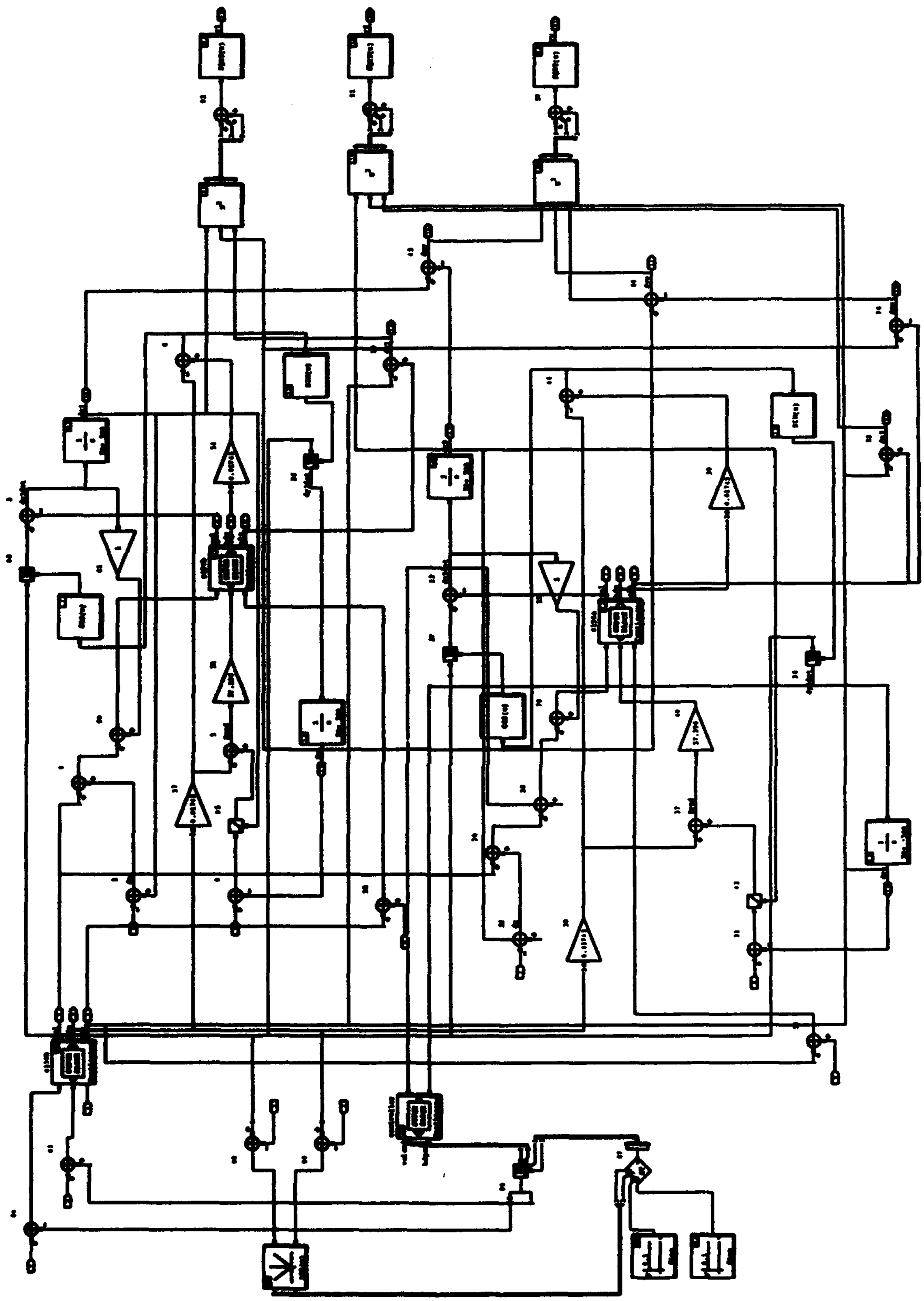

Figure 28 PI Controller and Logic Implementation

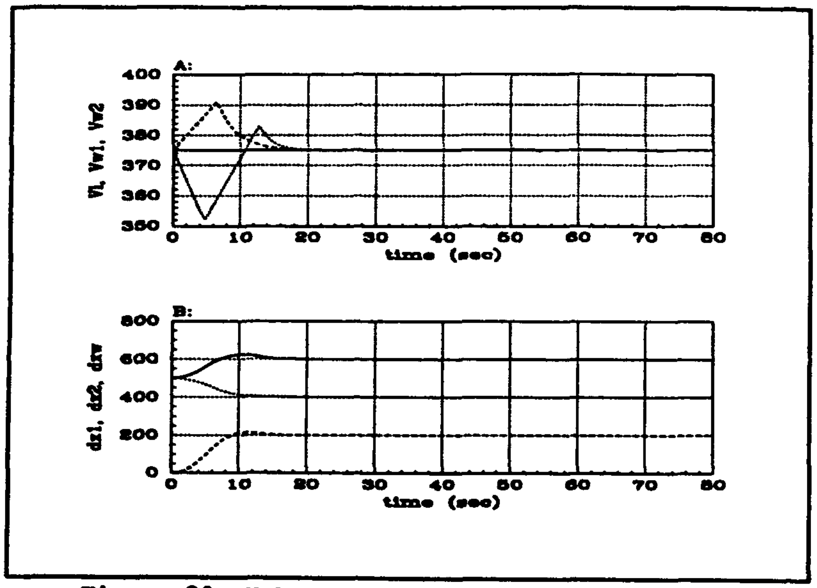

Figure 29 V Response To Controlled dx Input

V ANALYSIS OF CONTROLLED SYSTEM PERFORMANCE

This chapter presents the performance evaluation of the final formation control system. Portions of the basic operation of the system as examined in Chapter III is evaluated to examine improvements in performance. The axes reevaluated are those which received additional control as designed in the previous chapter. Test maneuvers as described in Section 2.5 are also performed. Plant models for the H-53 helicopter are substituted into the formation structure in the place of the C-130 fixed wing models and their operation examined. This provides a test of system and design robustness.

5.1 Basic 3-Ship Dissimilar C-130 Formation Performance

As accomplished in Chapter III for the uncontrolled or open loop formation model, basic performance of the formation model is repeated here for the controlled, 3-ship model with one dissimilar wing aircraft less capable than the lead and first wing aircraft (F4). Initial conditions and input magnitudes are as shown in Table 5. Performance of those axes which differ from the open loop system will be examined here, a complete set of response plots are included in Appendix B, Figures B-1 through B-18 are in the same format as those of the open loop performance shown in Chapter III, for comparison.

Figure 30A shows a smooth velocity response to a commanded formation velocity change. This response, when compared to the open loop response of the same input shown in Figure 16A, shows great improvement with no

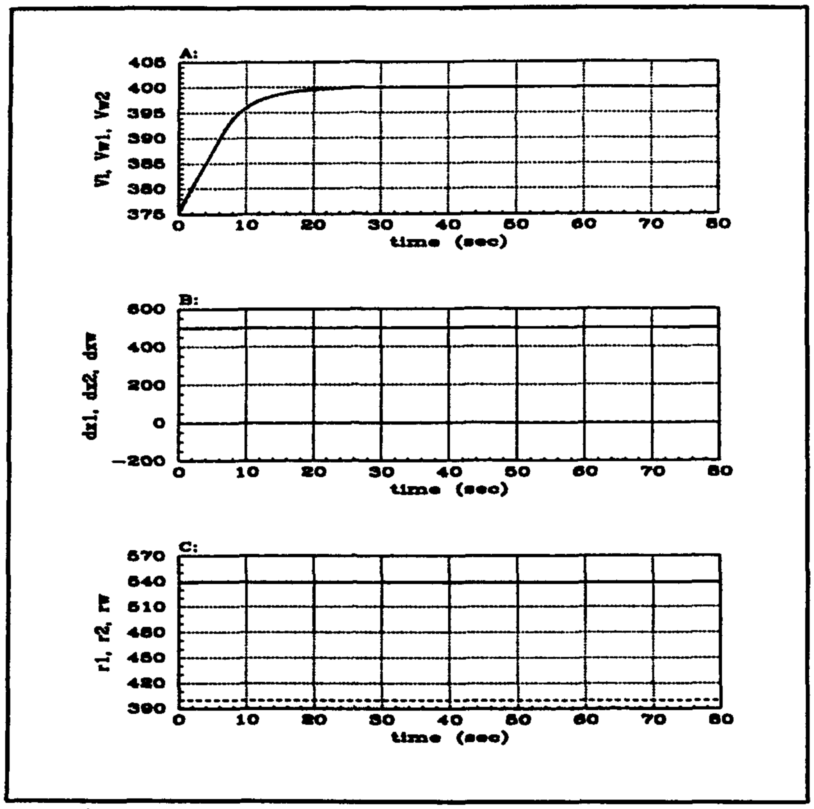

Figure 30 Response To Controlled V-lead Input

increase in response time. Longitudinal perturbation, shown in Figures 16B and 30B, has been reduced from 50 feet to essentially zero.

Figure 31 shows a similar improvement to a commanded change in longitudinal formation spacing. Velocities and separations shown in Figures 17 and 31 (A and B) respectively, exhibit reductions in oscillations as well as in overshoot magnitudes.

Figures 18 and 32 compare the response to a commanded change in formation heading. Although the response shown in Figure 32A is slower than that in Figure 18A, the overshoot in heading and the lateral separation deviation are both reduced in the controlled model.

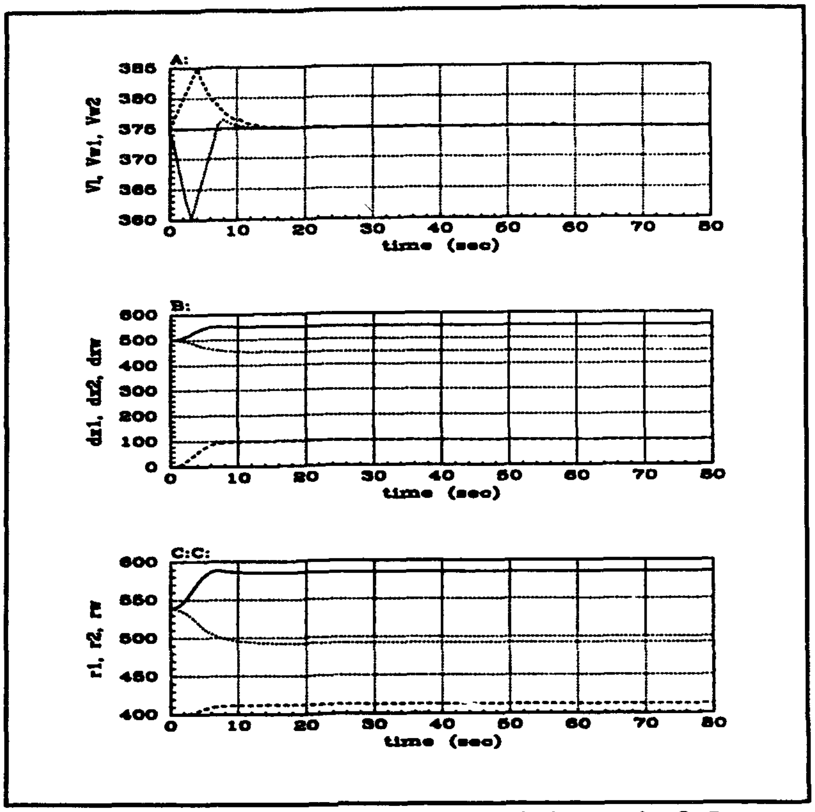

Figure 31 Response To Controlled dxw1, dxw2 Input

The response to a commanded change in lateral separation distance has not been affected by the insertion of the controller. Response shown in Figures 33 are equivalent to those in Figure 18. This illustrates that the logic used for the operation of the system controller, to enable the feed-back paths only when the lead aircraft is commanded a change, is effective. Otherwise, these responses would show unwanted differences.

5.2 <u>Formation Maneuver Evaluations</u>

Maneuvers described in Section 2.5 will be executed here for system evaluation. Input profiles for each maneuver are described below in their respective sections.

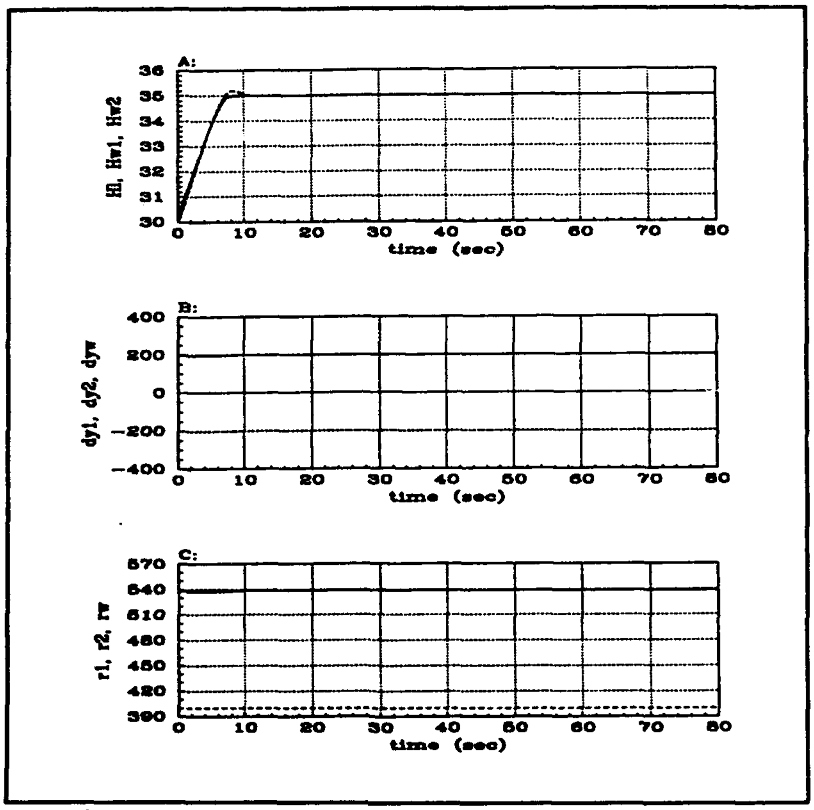

Figure 32 Response To Controlled H-lead Input

5.2.1 **Formation heading Change**. This maneuver is to be executed as a simple flat, formation turn as described in Section 2.5.1. Tactically, a formation maneuver such as this would include additional maneuvering by wing aircraft to conserve energy, this however, for simplicity is not accomplished here. The maneuver commanded is a 45 degree turn to the right, from 30 to 75 degrees magnetic heading. Of note here is that the less maneuverable aircraft is in the left wing position, the formation turns away from that aircraft. Controlled responses to a similar turn, to the left and into this aircraft is shown in Figure 26 from the previous section. Responses for this maneuver are shown in Figure 34. Note here that the overshoot for this turn is approximately 7 degrees. This is a result of the lead aircraft's attenuated signal to begin to reduce its

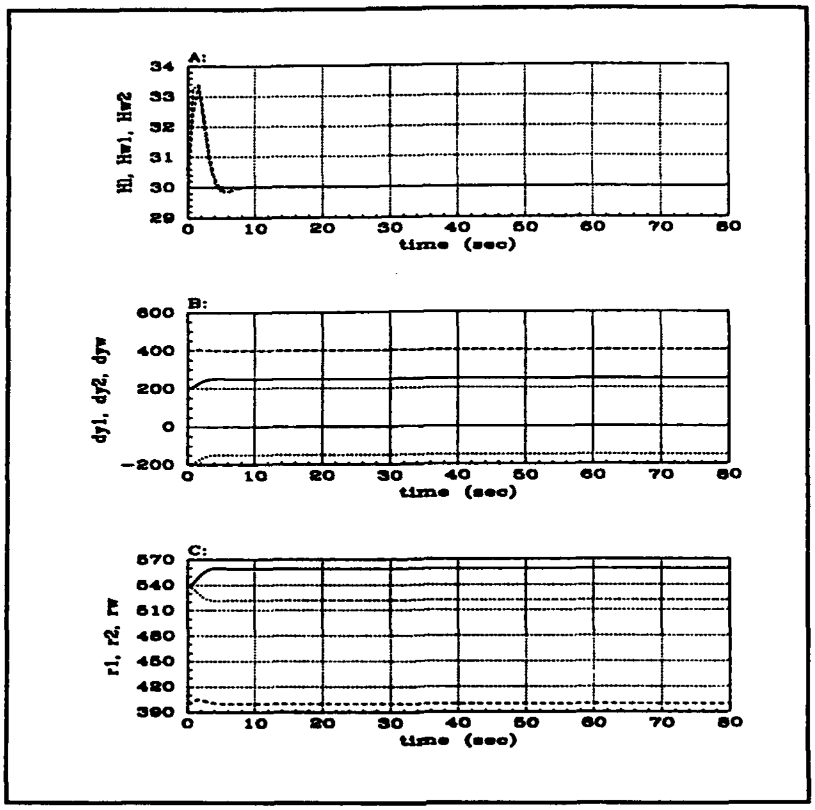

Figure 33 Response To Controlled dyw1, dyw2 Input

turn rate as the target heading is reached. In solving the problem of a less capable wing aircraft not being able to maintain formation through maneuvers, the lead aircraft is also less capable since its commanded maneuvers are attenuated. This result is clearly shown in figure 34A. However, as shown in Figures 34B and C, the lateral separation deviation is less than 50 feet throughout the maneuver.

5.2.2 **Terrain Clearance Maneuver**. This maneuver, uses an input profile of altitude required to clear a 300 foot high terrain obstruction. The aircraft is initially at an altitude of 500 feet AGL cruising at 375 ft/sec. An on-board system is assumed to provide altitude commands to clear the obstruction at 70 % of the aircraft's set clearance height of

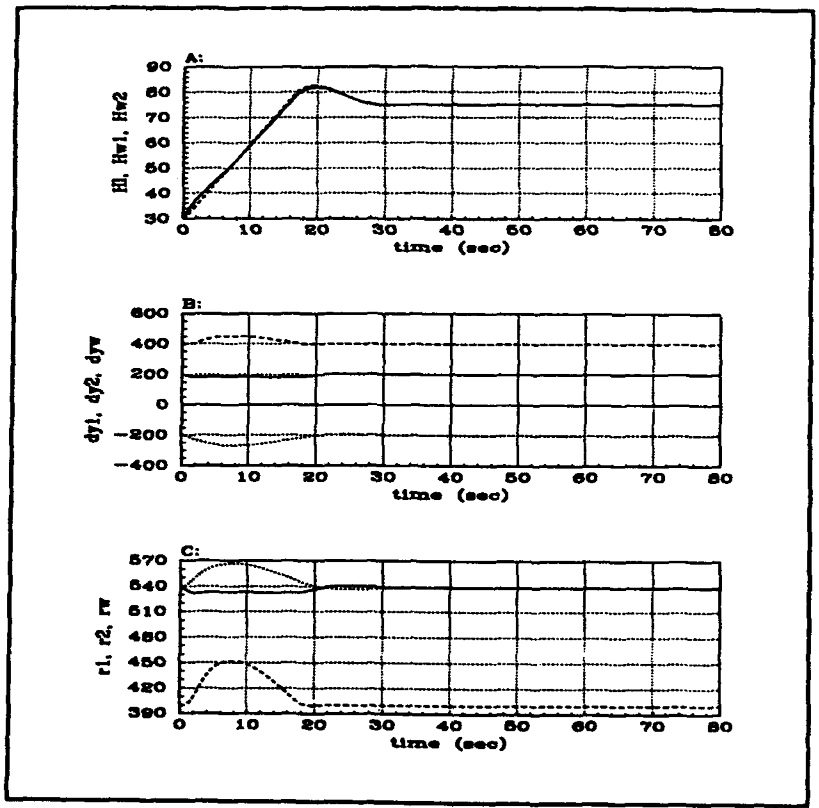

Figure 34 Response To Formation Turn

500 AGL, or 350 ft. The maximum altitude then is 300 ft for the obstruction, and 350 ft for clearance, or a total of 650 ft AGL. As the aircraft is already at 500 ft AGL, the total climb required is 150 ft.

The input profile is based on this total climb, and time to climb for the least maneuverable formation aircraft in climb capability. The input altitudes begin to increase in sufficient time for the aircraft with the slowest climb capability to reach the required altitude before the obstruction is reached. A near-side obstruction slope is assumed at 45 degrees. The actual input profile is based on a data stream of input altitudes at 0.4 second intervals at the formations nominal velocity. The input altitude profile, aircraft altitudes and vertical spacings are shown

in Figure 35A. Formation aircraft altitude responses are shown in Figure 35B showing individual wing aircraft maneuvering based on the lead aircraft, and not on each other. Vertical separation distances are shown in Figure 35C showing independence of the responses for the two wing aircraft.

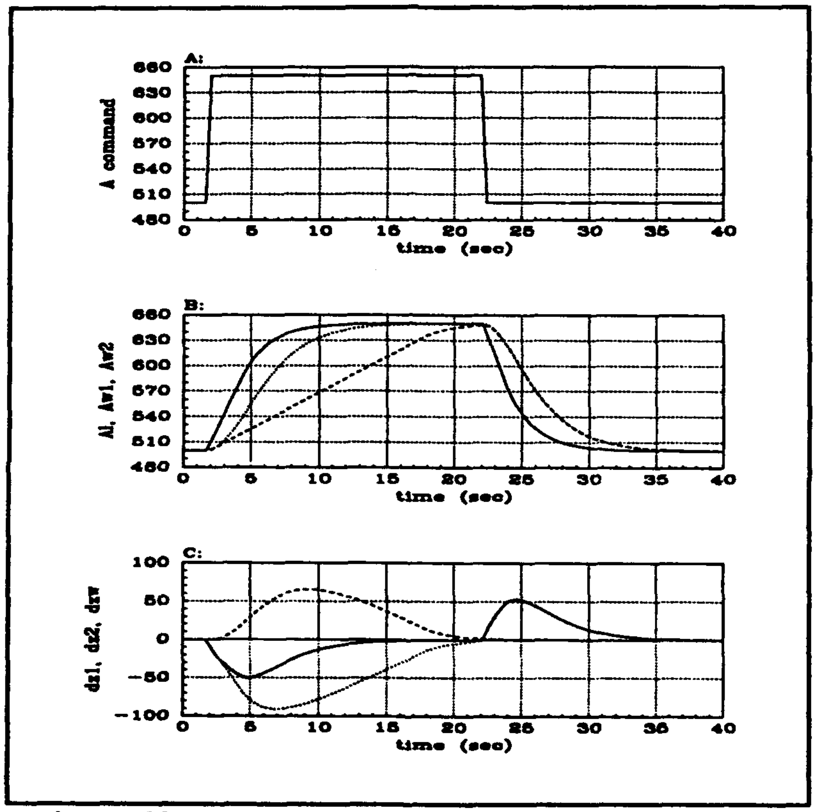

Figure 35 Response To Formation Terrain Clearance

5.2.3 **Formation Change - Trail to Diamond**. This maneuver is described in detail in Section 2.5.3. The formation is initially in a trail formation (dx1=500, dx2=1000, dy1=dy2=dz1=dz2=0) and is commanded to a diamond formation (dx1=500, dx2=500, dy1=200, dy2=-200, dz1=dz2=0). Longitudinal and lateral responses for this maneuver are shown in Figure 36. Figure 36B shows wing 2 accelerates into the new position

(decreasing dx from 1000 feet to 500 feet) in approximately 30 seconds, while simultaneously decreasing lateral separation from 200 feet to zero in approximately 7 seconds as seen in Figure 36D. Figure 36A shows an erroneous velocity response of wing 1 aircraft which is to remain at the same longitudinal position. This is due to the cosine term in the simulation which loses the correct sign in its calculation. It should show a slight increase in velocity during the turn-in. Even so, the responses show the maneuver to be completed accurately, quickly, and without chance for collision. Note Figure 36E shows the minimum absolute separation is reaches 400 feet which is the lateral separation between wing aircraft when they attain their new positions.

5.2.4 <u>Formation Change - Diamond to Trail</u>. This maneuver, also described in Section 2.5.3, is the opposite of the previous maneuver. The formation is commanded from a diamond pattern (dx1=dx2=500, dy1=200, dy2=-200, dz1=dz2=0) to a trail pattern (dx1=500, dx2=1000, dy1=dy2=0, dz1=dz2=0). Longitudinal and lateral aircraft responses are shown in Figure 37A - E. The velocity response shown in Figure 37A, and the longitudinal separation shown in figure 37B show that a change in longitudinal separation of this magnitude is not kept to a minimum deviation during the maneuver. Although, in this case, it is on the safe side since it is an increase in separation, not a decrease. The lateral separation, shown as heading in Figure 37C and lateral separation in Figure 37D, again attains the new target magnitude in less than 10 seconds. Note in Figure 37E, the absolute range between the two wing aircraft is reduced to less than 100 feet as they quickly turn-in while the wing #2 decelerates. This could possibly cause problems in other

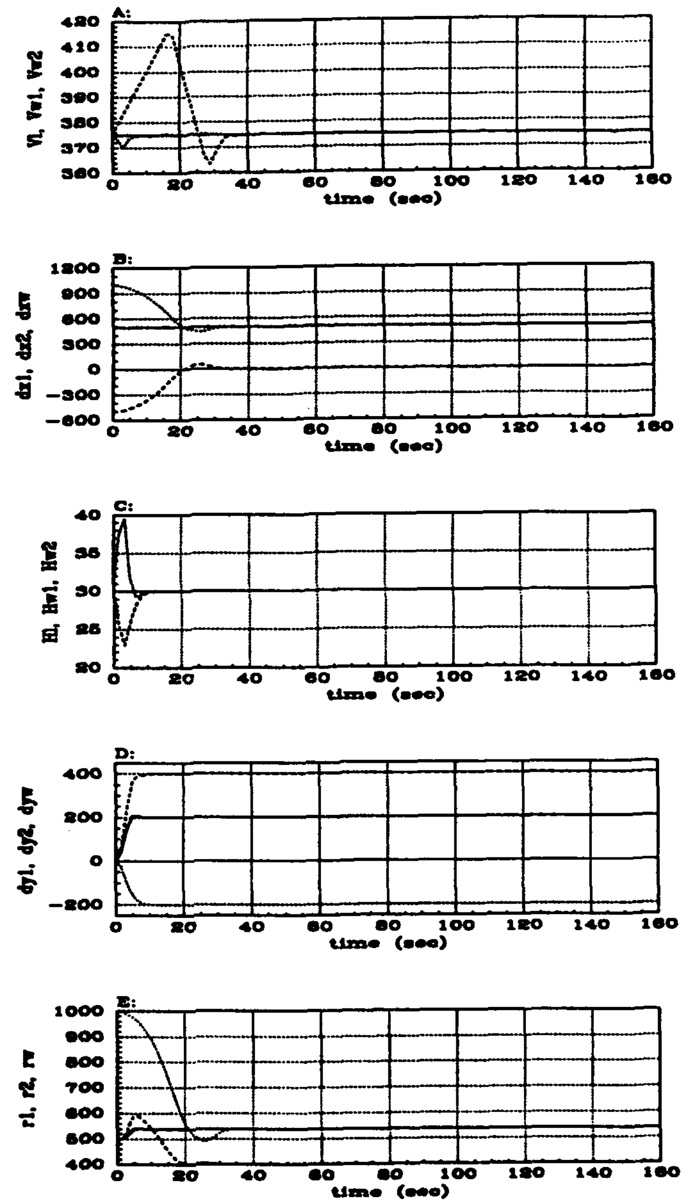

Figure 36 X Axis Response To Trail To Diamond Formation change

combinations of formation spacing changes. Perhaps this requires additional control between the wing aircraft.

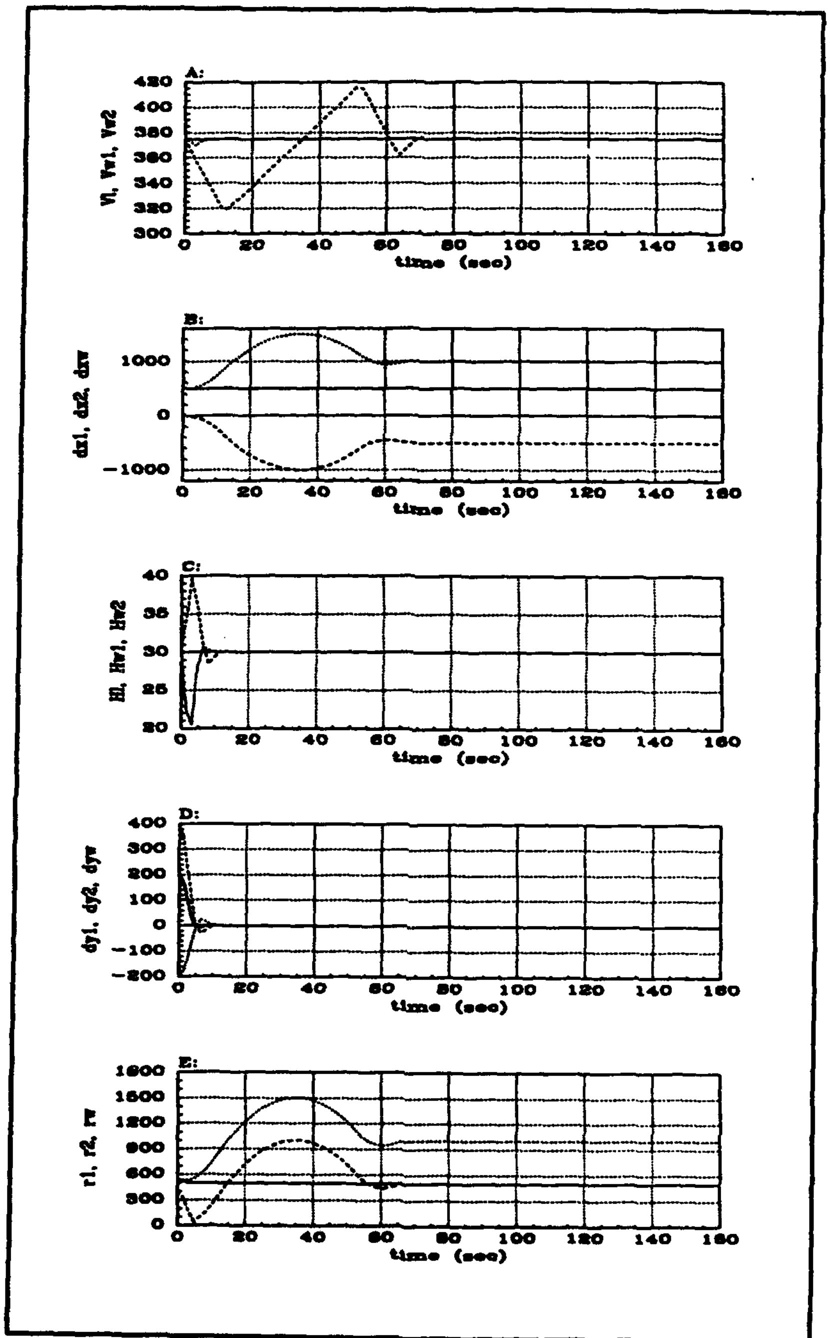

Figure 37 X Axis Response To Diamond To Trail Formation Change

5.3 Basic Helicopter Performance

This section describes the performance evaluation of the formation control system for robustness. The H-53 helicopter plant models, developed in Section 3.1.3, are inserted into the formation control system structure of formation 4 (F4) for evaluation. The formation is of three helicopters in a diamond formation. The lead and wing #1 helicopter, to the right, are of equal capabilities. The wing in position #2 is less capable than the lead or wing #1 aircraft. Basic performance is evaluated using the same heading, altitude and separation distance inputs used for the C-130 evaluation with exception to velocity, as the H-53 flies at a slower velocity than the C-130. The nominal velocity for H-53 evaluations is 160 ft/sec, which corresponds to approximately 100 knots. Responses are shown in Figures C-1 through C-36 in Appendix C. Plots are not included here for analysis but comments are made relating to the plots in Appendix C.

Responses to all basic inputs in the longitudinal, lateral, and vertical channels shown in Figures C-1 through C-18, exhibit performance as good as those in the C-130 evaluation. All responses are smooth, rapid, and cause no problems in terms of reduced separation distances or danger. Figure C-19 shows the response to a formation turn, again of note is the problem of the cosine term's effect on velocity. It shows the velocity of the least capable helicopter, during a formation turn away from that helicopter. The actual response initially increases during the turn, as that particular helicopter is on the outside of the turn. The simulation computation of the cosine term loses the sign, so both increases and decreases in velocity are shown here as negative. In Figure

C-19, the first deviation in velocity of the dashed line, should actually be positive.

Figure C-21, shows the heading response during the formation turn. The slight non-uniformities in the response are due to the combination of proportional and integral gains used in the feed-back controller. These can be optimized to get a uniform response if required. As in the C-130 evaluation, this maneuver shows a good response with just over 2 degrees overshoot, less than 50 feet lateral displacement as seen in Figure C-22, and less than 30 feet absolute range deviation as seen in Figure C-23.

Figures C-25 and C-26 show a much faster response to the ridge crossing, however the input profile was not created based on the helicopter's slower ground speed. The plot clearly shows an accurate response with plenty of time available to clear the obstruction. Figures C-27 through C-36 illustrate the formation control system controls the helicopters from one formation to another as well as it did the fixed wing aircraft. All responses are smooth, direct, and cause no danger of collision between the lead and wing aircraft, or between the wing aircraft themselves.

VI ANALYSIS & CONCLUSIONS

6.1 Analysis of Results

The objective of this research was to develop a fully coupled, automated formation control system, capable of controlling a number of like or dissimilar aircraft in maneuvering, formation flight. That objective has been shown to be attainable, and was met.

Results of this research support the premise of being able to control formations of like or dissimilar aircraft with a fully coupled multi-level, multivariable control strategy as described in this report. Numerous additional requirements are involved in controlling and monitoring the operation of multiple aircraft, especially when they differ in capabilities. However, adequate control can be accomplished without severely restricting overall formation performance.

This research answered numerous questions. This type of control can be accomplished with minimum effect on the maneuverability of the formation as an entity in itself. Formations of dissimilar aircraft can be controlled in a safe and effective manner by a system with minimum feed-back to the leader of that formation. Maneuvers are effectively executed by controlling the input commands for those maneuvers, without placing controls on the aircraft plants themselves.

6.1.1 Basic Formation Operation. As developed in Chapter II and simulated in Chapter III, formations of like and dissimilar aircraft can, to a degree, perform without additional lead aircraft control. However,

this open loop operation is restricted to small magnitude changes and maneuvering. Beyond these, problems with formation spacing become dangerous, especially with dissimilar aircraft in the formation. Large magnitude formation inputs are shown to cause collisions or lose less capable aircraft out of the formation.

6.1.2 Controlled Formation Performance. The requirement for additional control on formation maneuvering is developed in Chapter III. A formation system controller is developed in Chapter IV and its performance evaluated. This controlled performance illustrates how additional control, through a simple PI feed-back controller, profoundly improves system performance and makes it possible for this type of a control system to operate effectively. Essentially all problems caused by dissimilar aircraft in the same formation are eliminated without reducing the maneuverability of the entire formation. The control structure and strategy is shown robust by exchanging the fixed wing C-130 simulation models, for H-53 helicopters. Performance of this formation is as good as those originally examined with the C-130s.

6.2 Conclusions

Upon evaluating the results of this study, several solid conclusions can be drawn.

--- A formation such as developed here, can operate to some extent in an open loop manner. However, no assurance is available as to the outcome of specific maneuvers to be executed by that formation. Small magnitude inputs are accomplished, but no limit is made on those small magnitudes

and how they relate to separation distances. At some point, a combination of separation distances and commanded maneuver magnitudes will cause either a collision, or a less capable aircraft to be lost from the formation.

--- A level of feed-back, provided to the formation control system through a PI controller, can be used to effectively attenuate lead aircraft or formation level inputs such that a less capable aircraft is not out-maneuvered. This makes automated, coupled, dissimilar aircraft formation flight possible.

--- The approach to formation control undertaken in this study, provides a robust system independent of the particular aircraft in the formation, how the formation is configured, or formation level commanded maneuvers. Formation inputs are attenuated based on relative maneuvers of formation aircraft.

--- Aircraft separation is insured using a common reference for all formation aircraft. As all aircraft are keying from the same lead aircraft, second order effects of aircraft responses are eliminated.

Although the idea of an operational, fully automated system may be a long way from aircraft used today by Special operations Forces, this study lays the ground work for a vast array of studies made possible by developments of this study. The results of this research provide the far end of measuring stick (future possibilities), with a manual system flown by pilots with their eyes out the window and their stick in their hand as

the near end, (today's reality). Numerous trade-offs and studies are now possible to evaluate an infinite number of points along that continuum, to bridge the gap between manual formation control and fully automated and coupled systems to provide pilots with valuable assistance in performing the arduous task of formation flight.

6.3 Recommendations for Further Study

This research is a first along the lines of formation control of this nature, and accomplished in this manner. Numerous possibilities for additional research exist and have come to light during this research. Some of these come from limitations and assumptions made for this research, and some expand on the order of models used for simulation purposes. Several of these areas are described below.

Higher order aircraft models should be incorporated into these formation models for a more precise look at the operation of these formations. Actual sensor models should be incorporated into these formations to allow evaluation of particular sensors used, or for formation spacing and control capability requirements studies.

This research assumes continuous control systems, controlled by continuous measurements of relative positions between aircraft. This data stream should be degraded to simulate a discrete stream of measurement data and a more realistic look at performance. Time delays should be incorporated into the feedback paths to simulate discrete measurements at particular update rates. These update rates will allow correlation between sensor requirements and formation spacings for particular aircraft.

Probably the most important assumption of this research is that of a fully coupled automated control system capable of controlling all axes on individual aircraft within the formation. Few pilots today would comfortably relinquish full control to an autopilot during low level or maneuvering formation flight. A more realistic system would offer additional control on a single axis or a combination of axes while leaving a level of control up to the pilot.

The results of this study form a basic beginning block upon which a study, such as proposed, is easily built. Pilot models should be added to control channels individually and in combinations. This pilot in the loop evaluation leads directly to a look at performance degradation, from these results, an optimum combination of pilot, autopilot blending can be evaluated, or metrics leading to that measurement can be devised.

Appendix A: Formation Models and Basic Uncontrolled Responses

This appendix contains block diagrams of the limited aircraft models and formation models developed for this study. Basic, open loop (uncontrolled) responses of the performance of these models is included for reference. Initial conditions, input values, and outputs of interest for each input are shown in Tables 4 through 7 in the report. Models were developed using the work-station version of MatrixX on a Sun 'Unix' work-station.

The plots contained in this appendix depict individual aircraft reponses, and formation spacings in response to formation level inputs. Plots are consistent in notation as described in the text of this report. The plots in this appendix are arranged as follows.

LEGEND FOR ALL PLOTS

1st parameter : Solid line (----------)

2nd parameter : Dotted line (············)

3rd parameter : Dashed line (- - - - -)

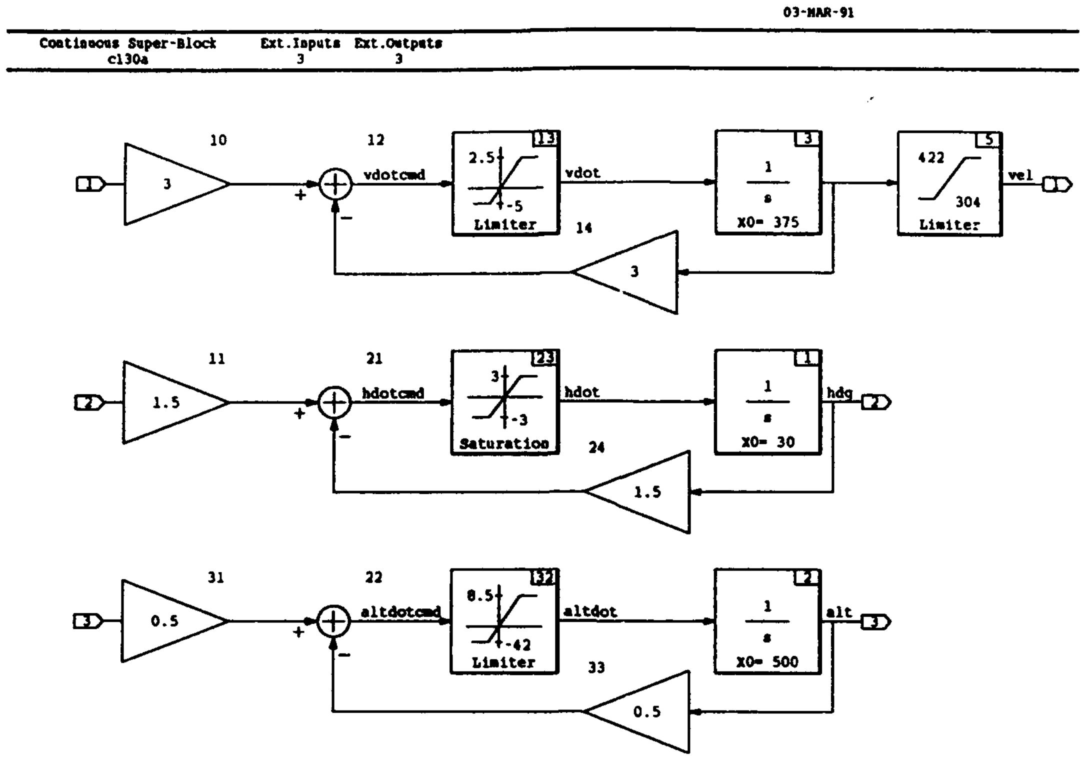

Figure A-1: Limited C-130 Model (a)

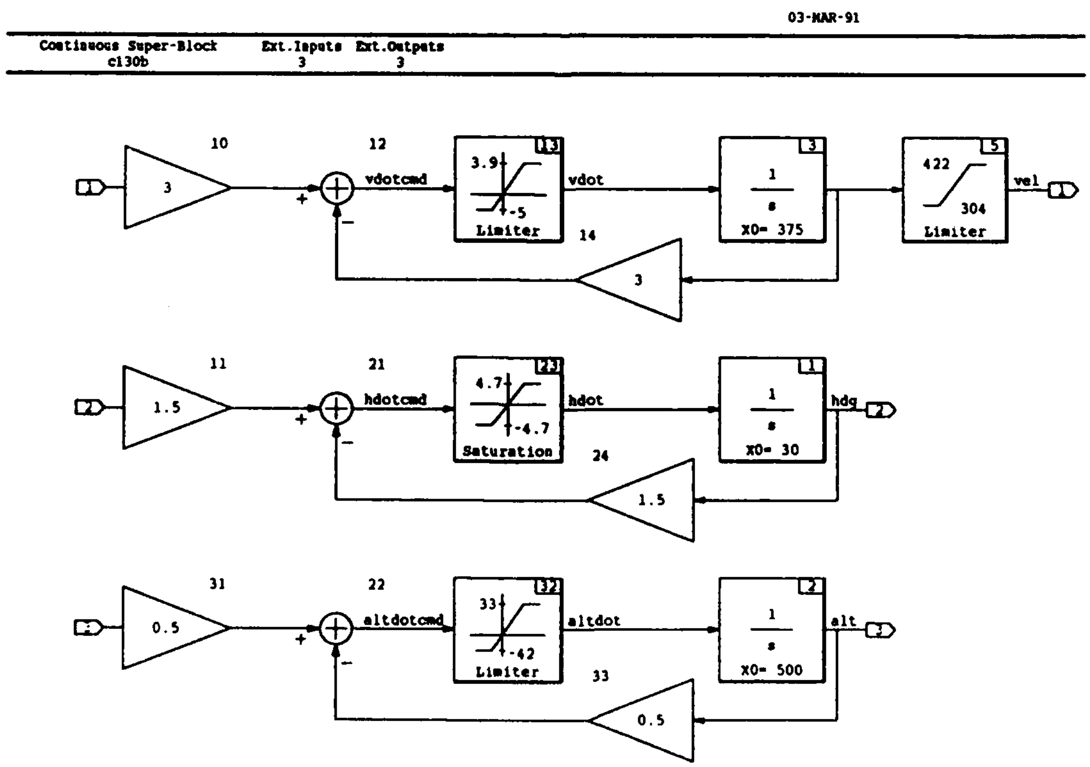

Figure A-2: Limited C-130 Model (b)

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Continuous Super-Block	Ext.Inputs	Ext.Outputs
h53a	3	3

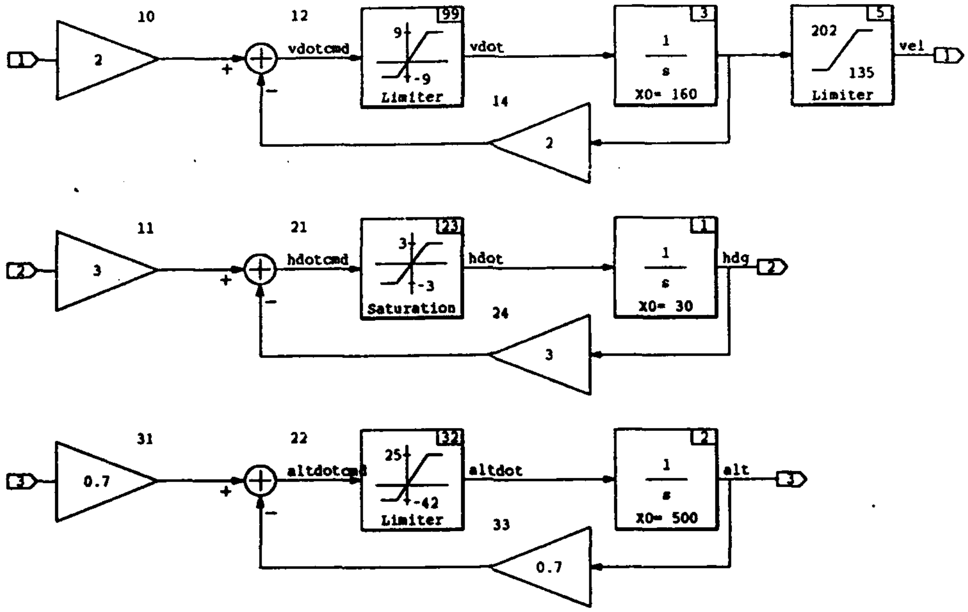

Figure A-3: Limited H-53 Model (a)

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Continuous Super-Block	Ext.Inputs	Ext.Outputs
h53b	3	3

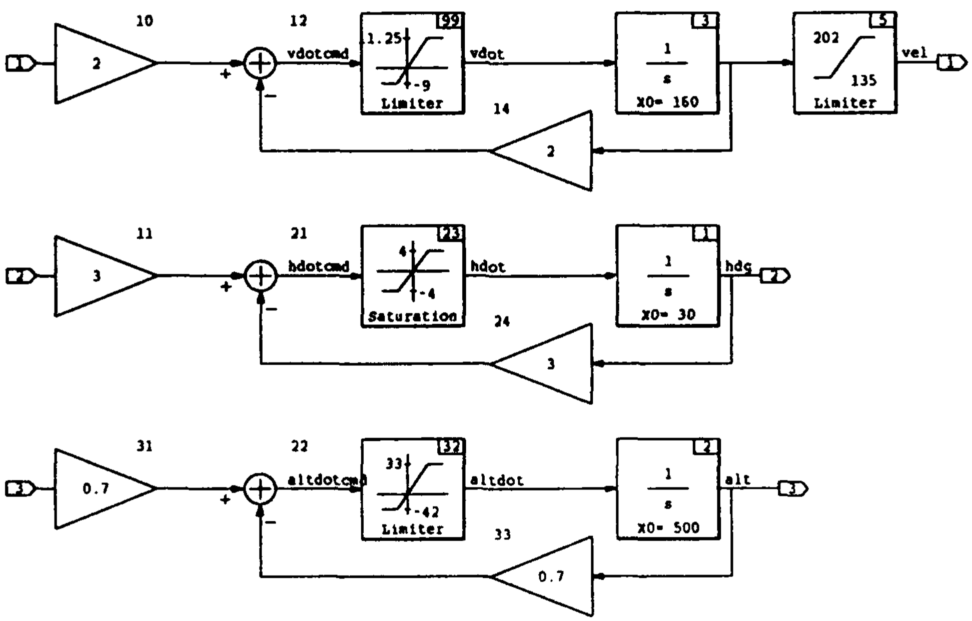


Figure A-4: Limited H-53 Model (b)

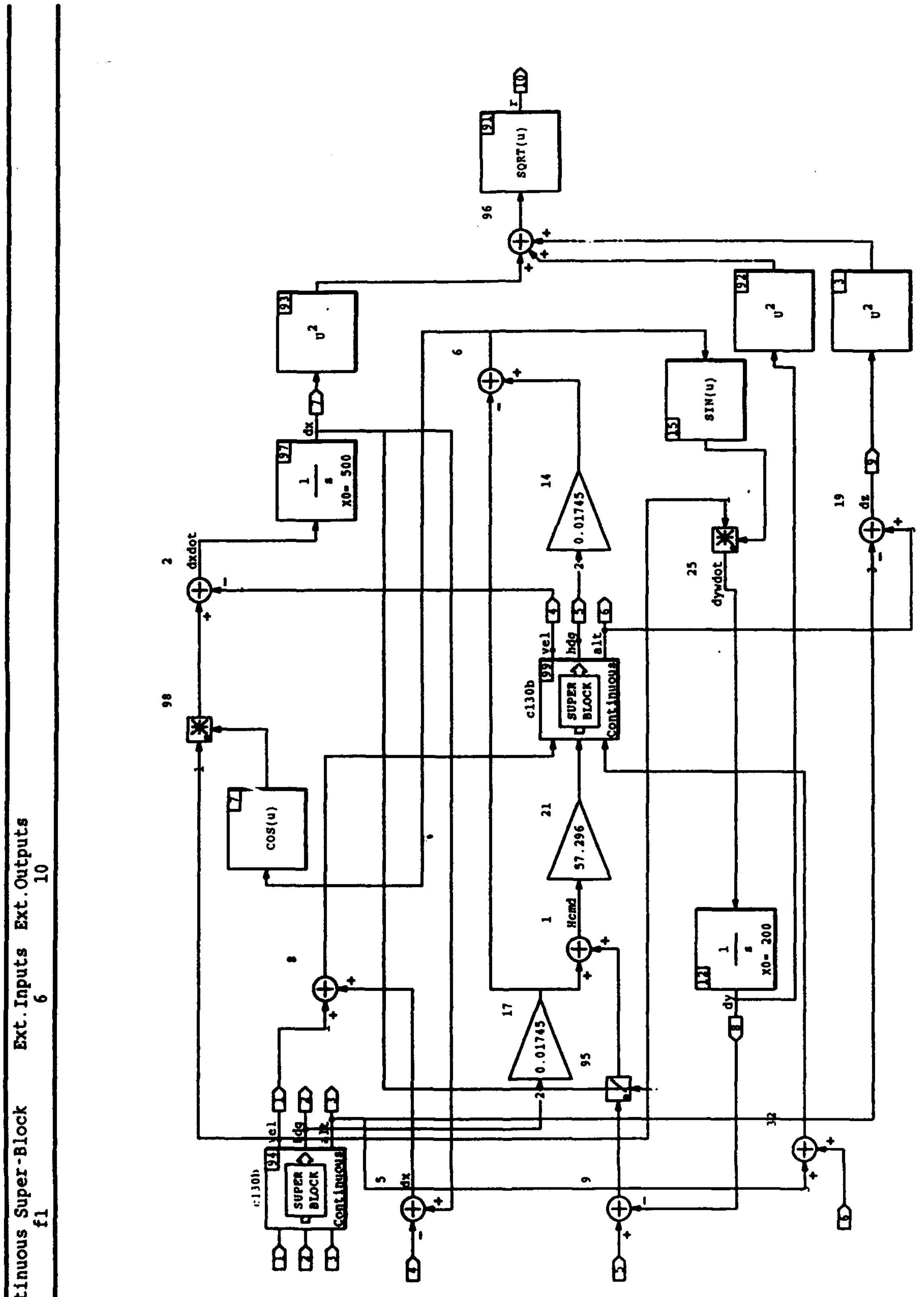


Figure A-5: Basic 2 Ship Formation Model (F1)

Figure A-6: F1; V input, V resp

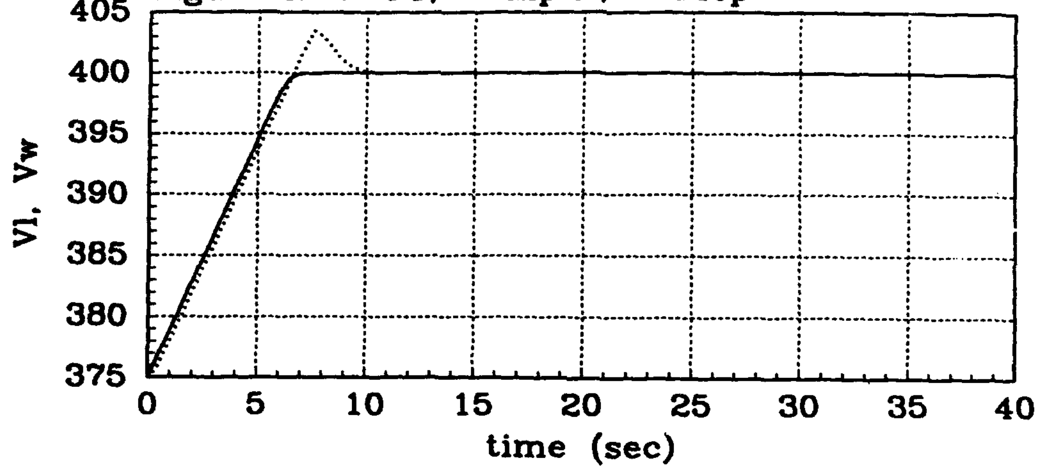
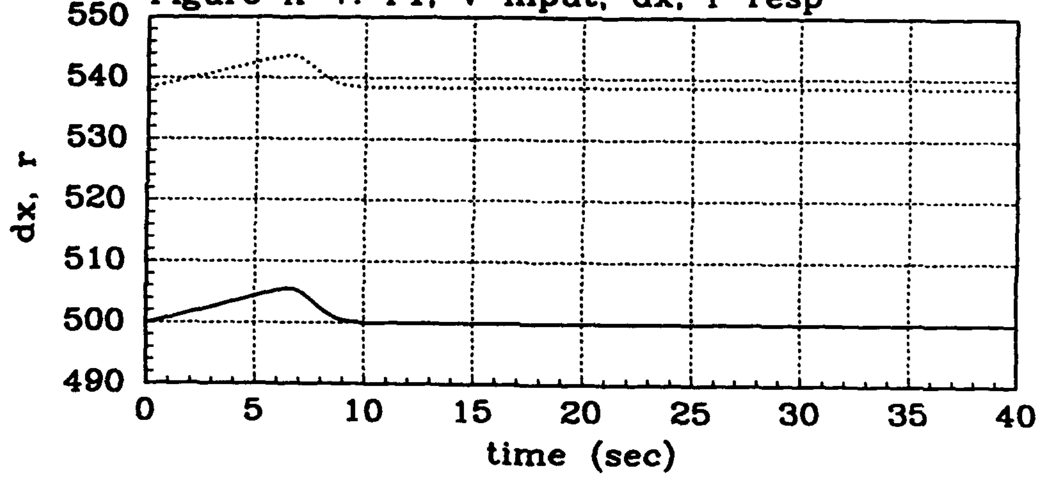


Figure A-7: F1; V input, dx, r resp



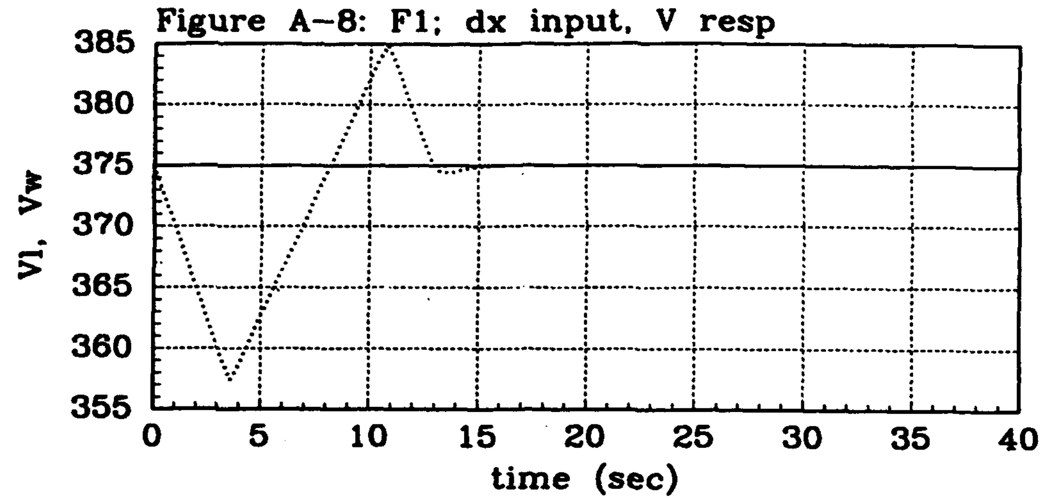


Figure A-8: F1; dx input, V resp
V1, Vw
385
380
375
370
365
360
355
0
5
10
15
20
25
30
35
40
time (sec)

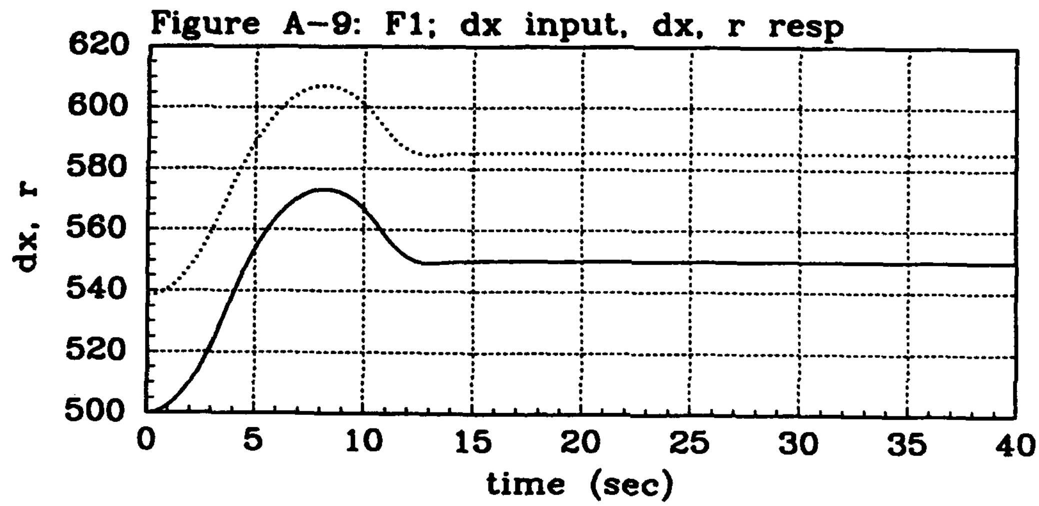


Figure A-9: F1; dx input, dx, r resp
dx, r
620
600
580
560
540
520
500
0
5
10
15
20
25
30
35
40
time (sec)

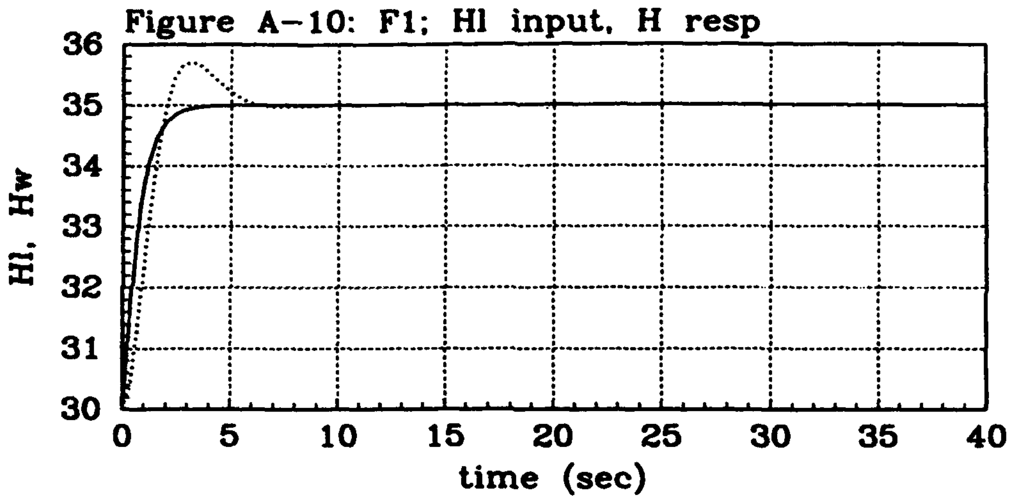


Figure A-10: F1; Hl input, H resp
Hl, Hw
36
35
34
33
32
31
30
0
5
10
15
20
25
30
35
40
time (sec)

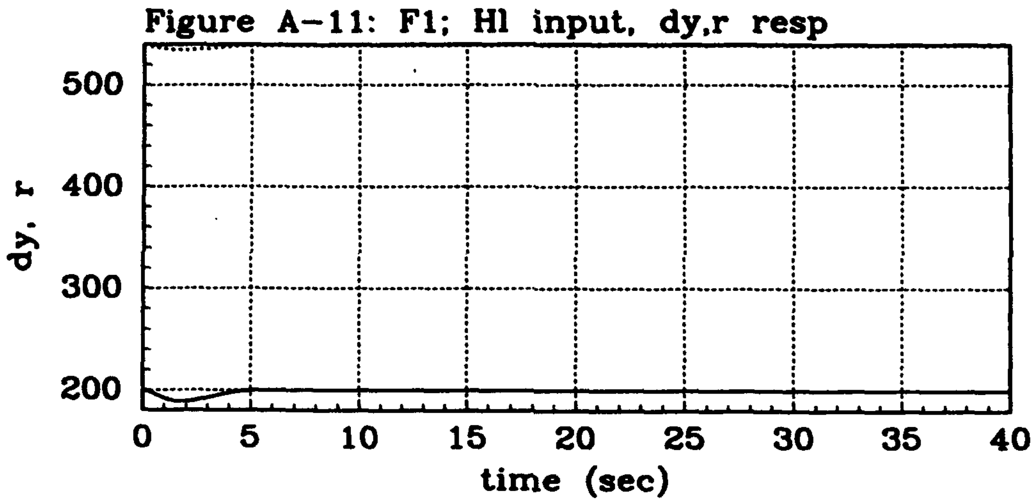


Figure A-11: F1; Hl input, dy,r resp
dy, r
500
400
300
200
0
5
10
15
20
25
30
35
40
time (sec)

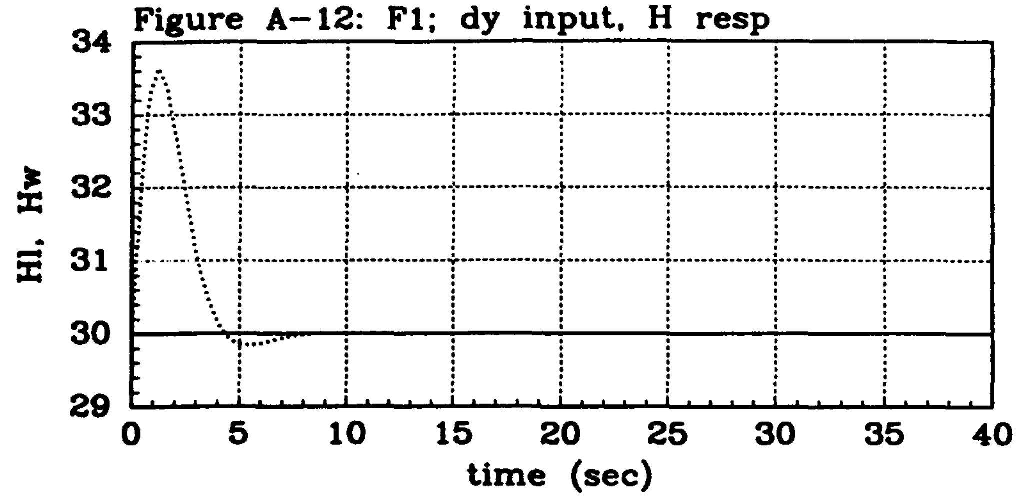


Figure A-12: F1; dy input, H resp
34
33
32
31
30
29
Hl, Hw
0
5
10
15
20
25
30
35
40
time (sec)

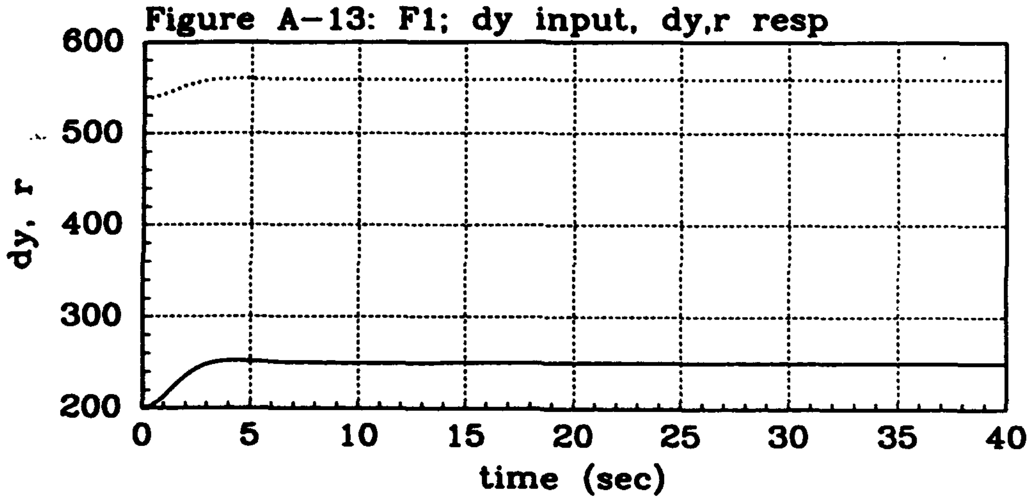


Figure A-13: F1; dy input, dy,r resp
600
500
400
300
200
dy, r
0
5
10
15
20
25
30
35
40
time (sec)

Figure A-14: F1; A input, Al,Aw resp

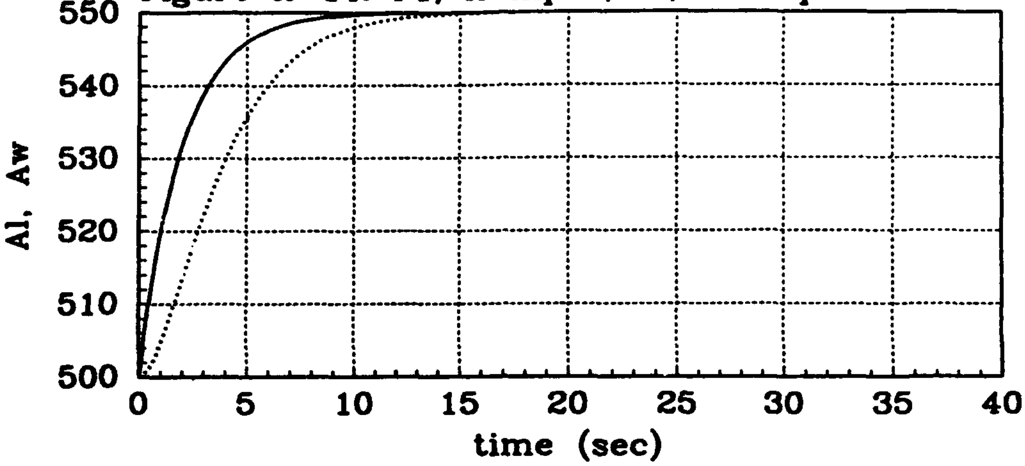


Figure A-15: F1; A input, dz,r resp

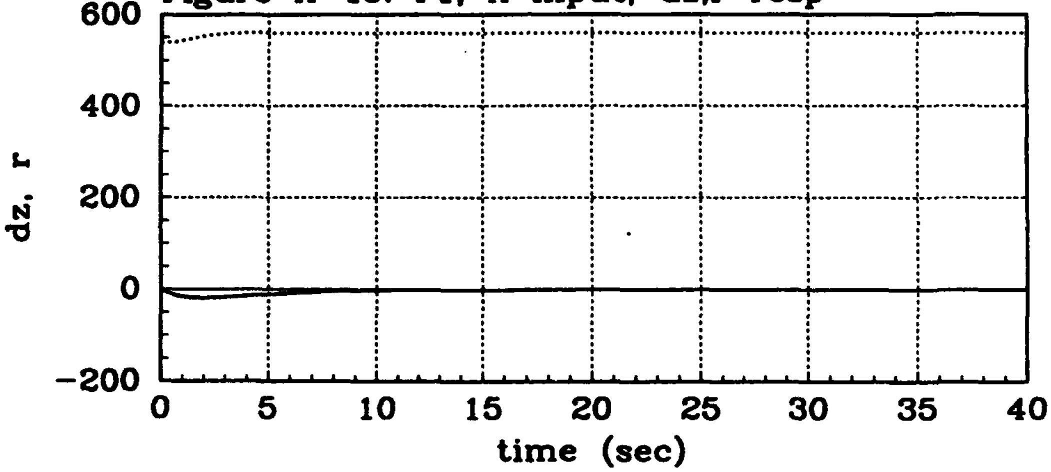


Figure A-16: F1; dz input, A resp

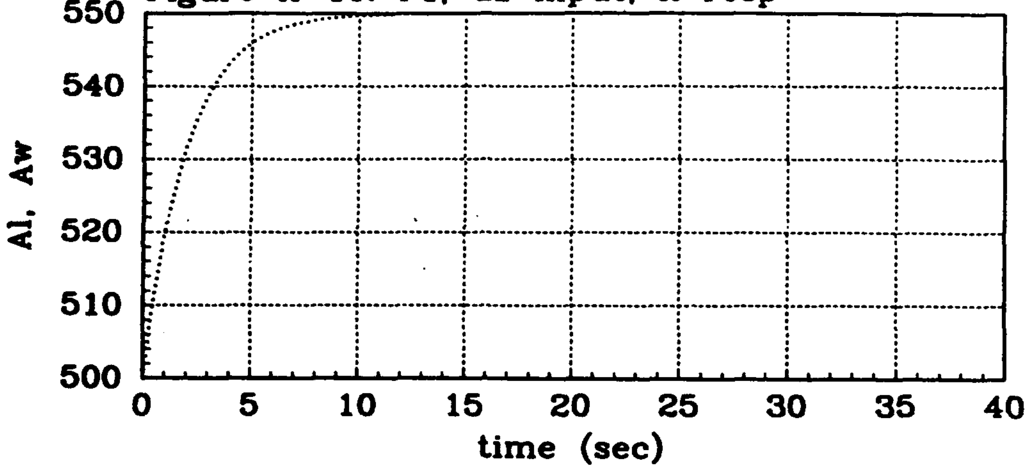
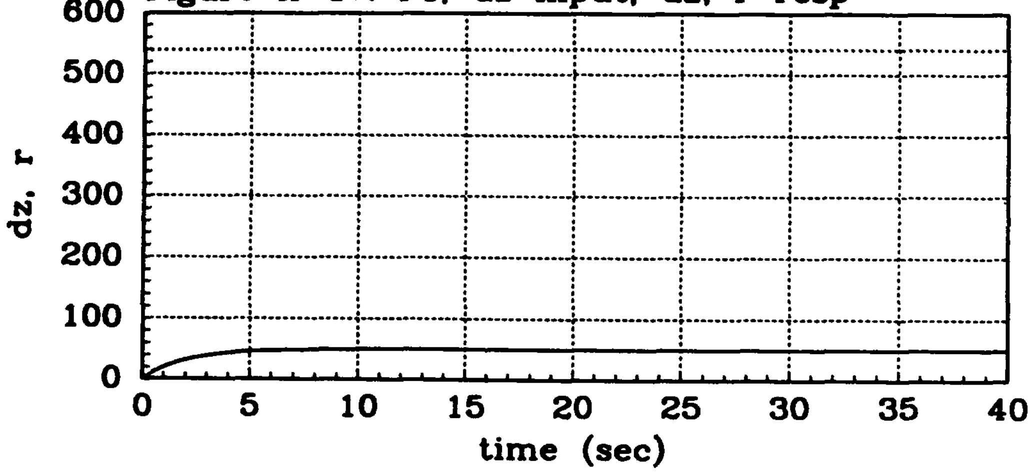


Figure A-17: F1; dz input, dz, r resp



Continuous Super-Block
f2

Ext.Inputs 6

Ext.Outputs 10

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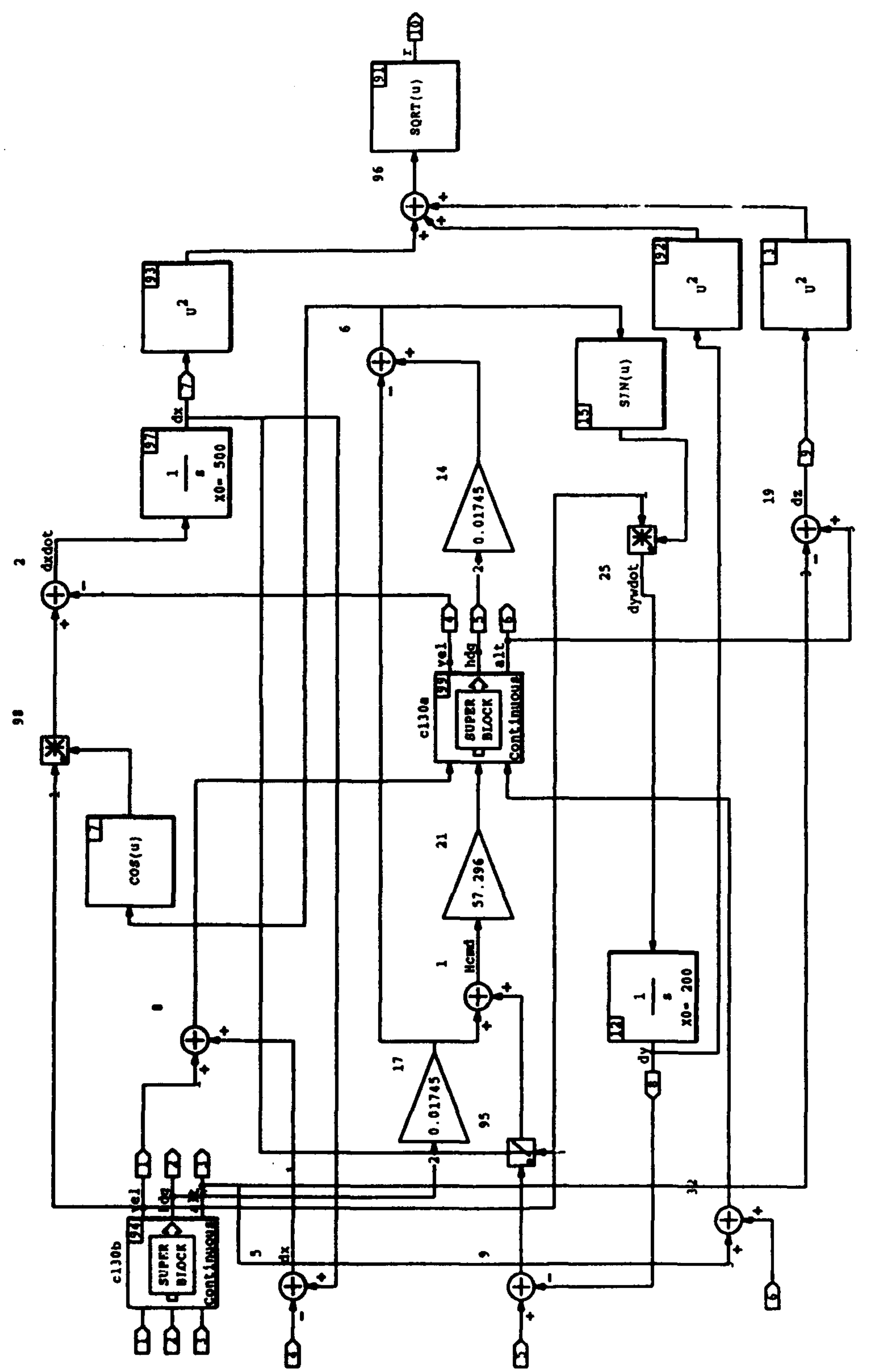


Figure A-18: Basic 2 Ship, Mixed Formation Model (F2)

Figure A-19: F2; Vl input, V resp

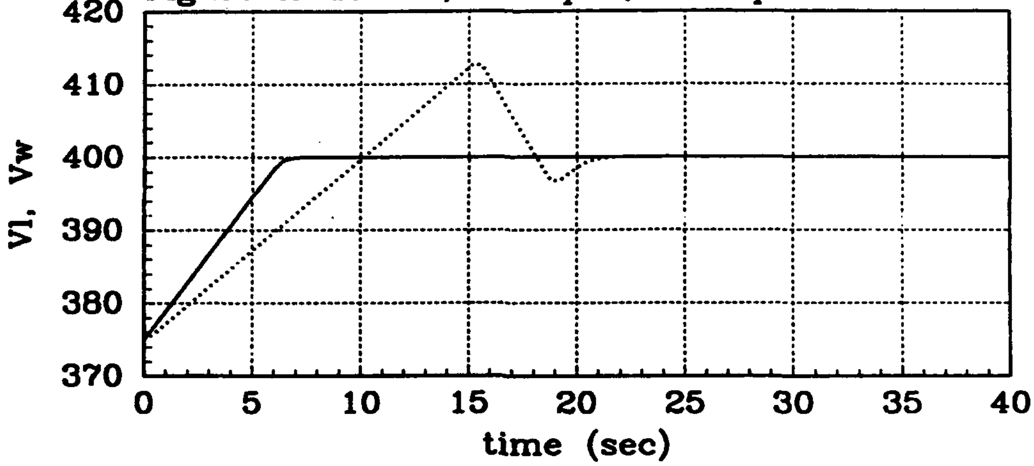
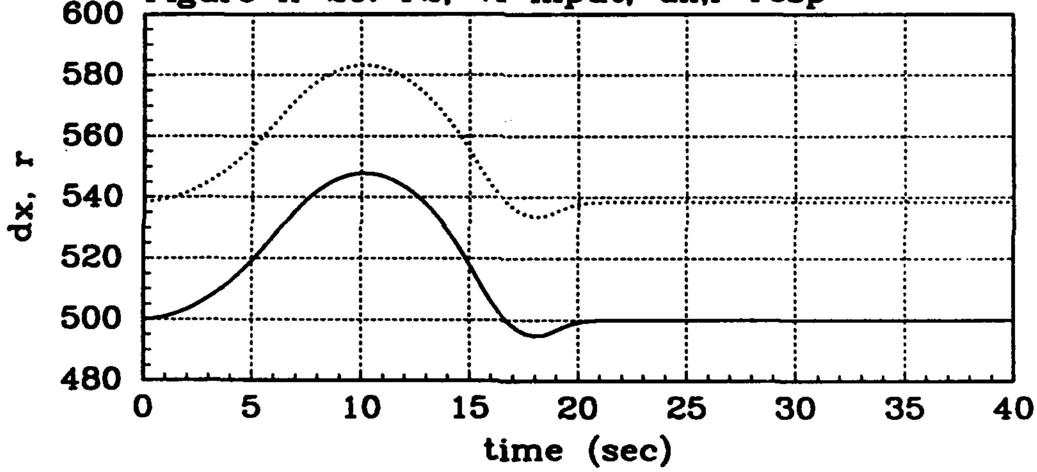


Figure A-20: F2; Vl input, dx,r resp



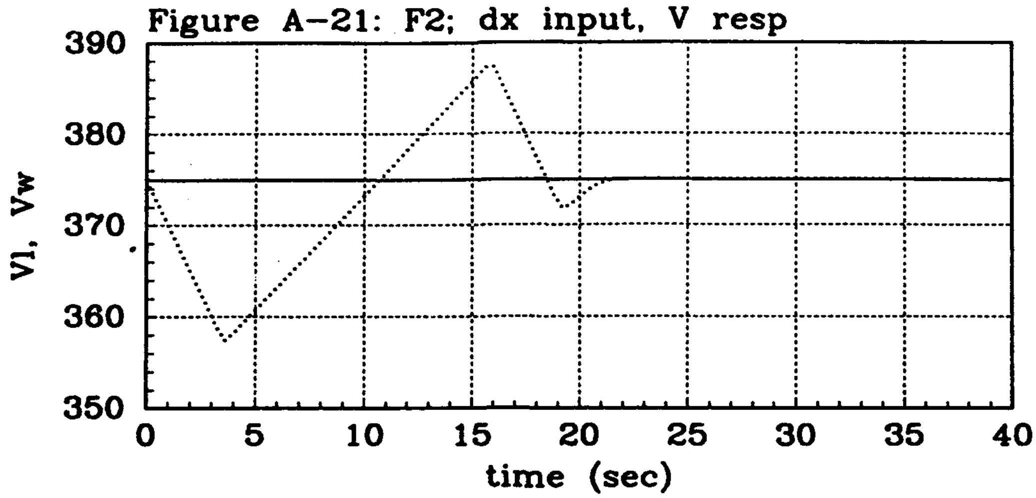


Figure A-21: F2; dx input, V resp
390
380
370
360
350
Vl, Vw
0
5
10
15
20
25
30
35
40
time (sec)

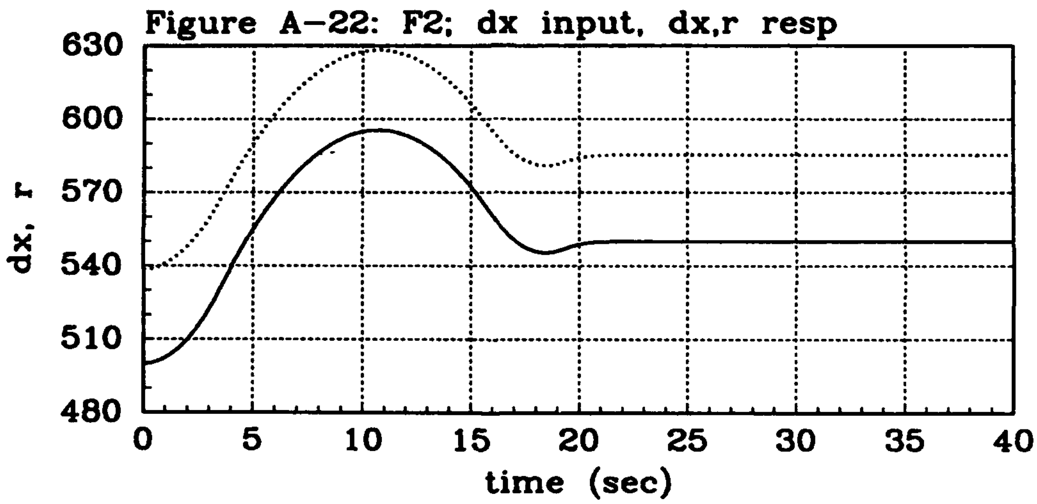


Figure A-22: F2; dx input, dx,r resp
630
600
570
540
510
480
dx, r
0
5
10
15
20
25
30
35
40
time (sec)

Figure A-23: F2; Hl input, H resp

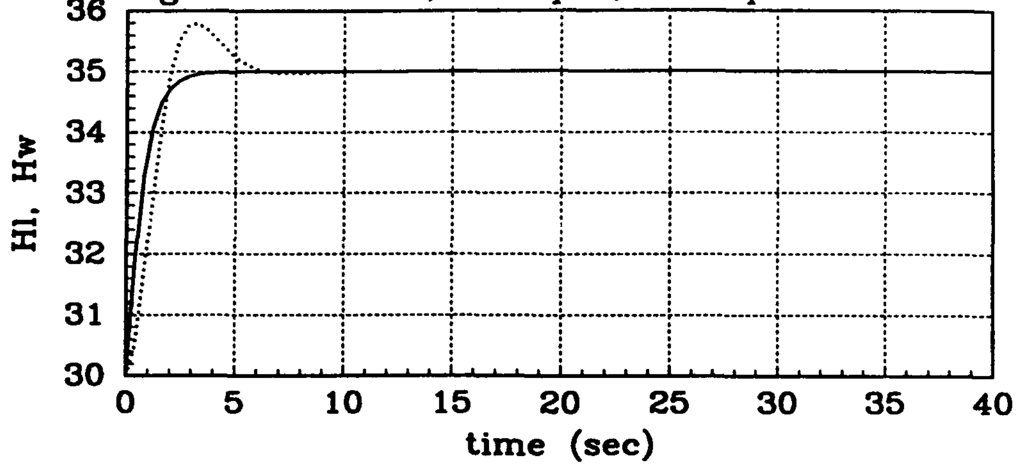
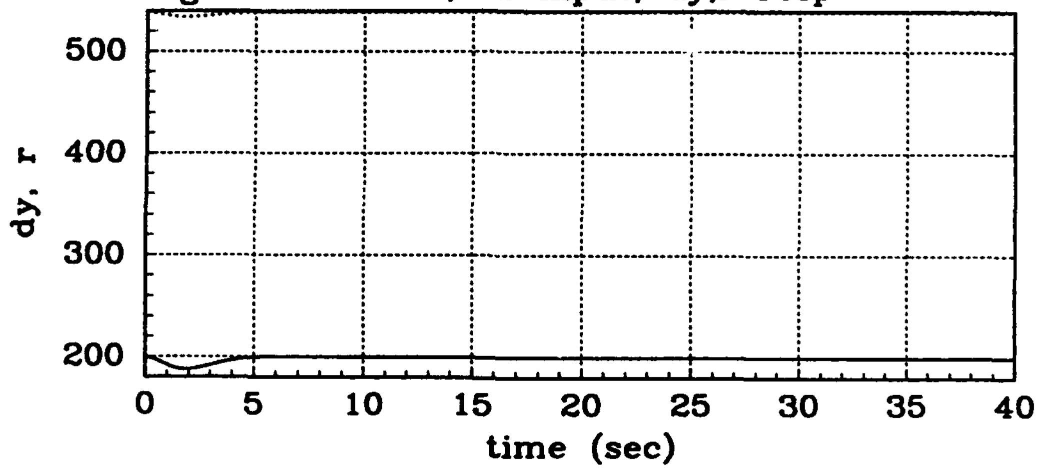


Figure A-24: F2; Hl input, dy,r resp



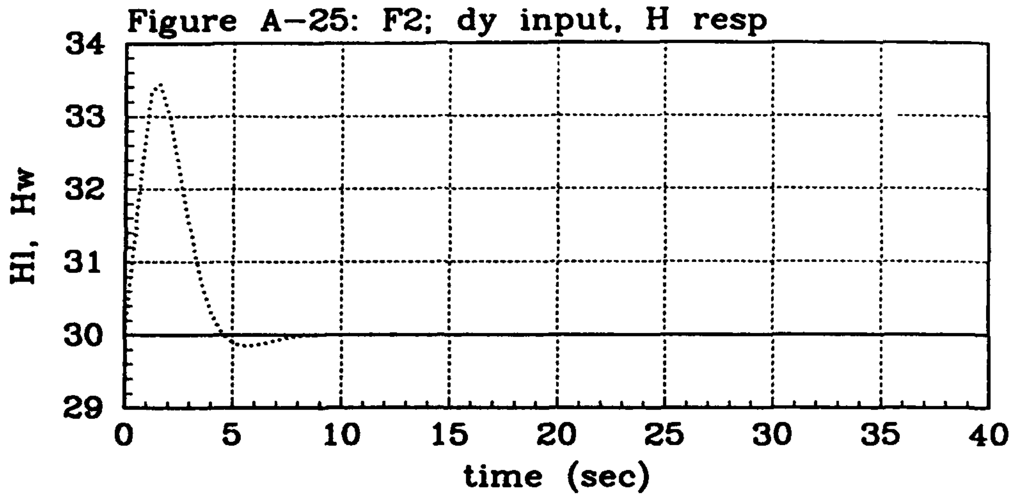


Figure A-25: F2; dy input, H resp
Hl, Hw
34
33
32
31
30
29
0
5
10
15
20
25
30
35
40
time (sec)

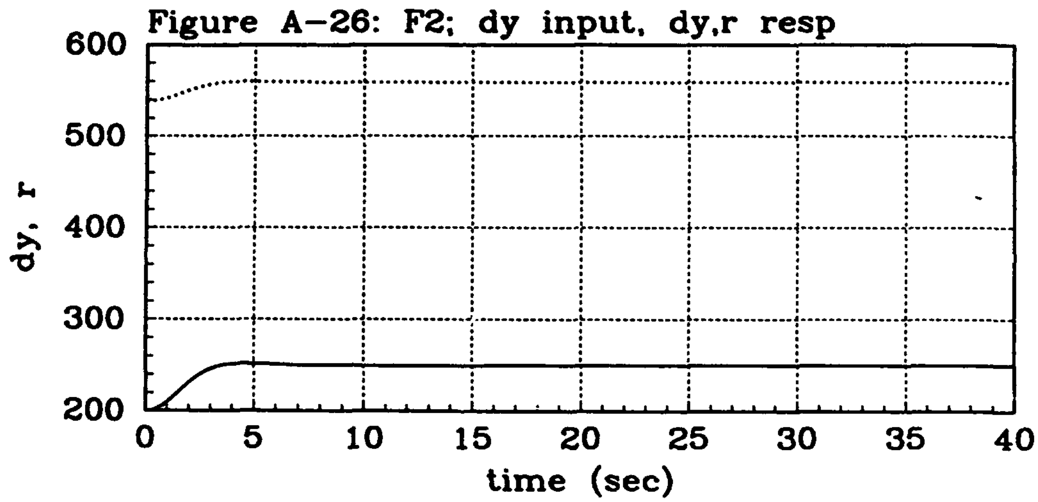


Figure A-26: F2; dy input, dy,r resp
dy, r
600
500
400
300
200
0
5
10
15
20
25
30
35
40
time (sec)

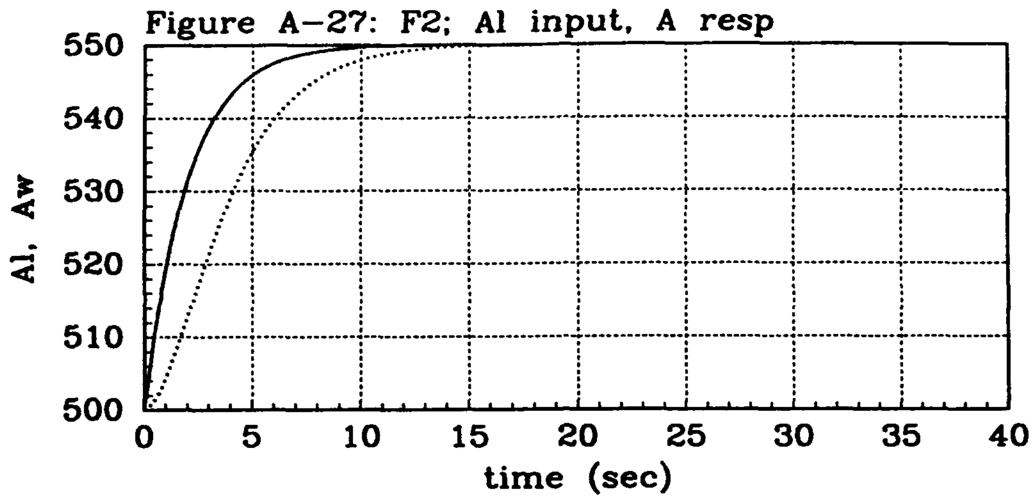


Figure A–27: F2; Al input, A resp
550
540
530
520
510
500
Al, Aw
0
5
10
15
20
25
30
35
40
time (sec)

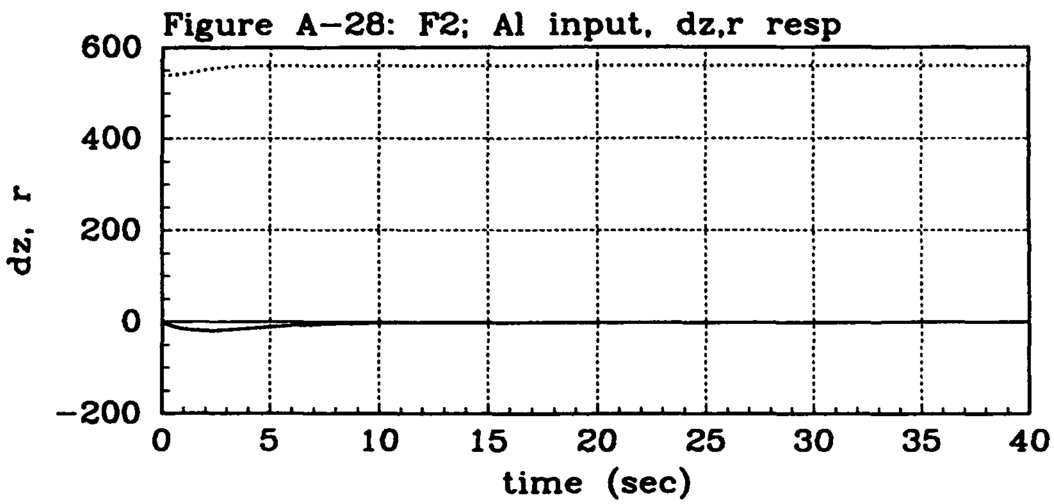


Figure A–28: F2; Al input, dz,r resp
600
400
200
0
–200
dz, r
0
5
10
15
20
25
30
35
40
time (sec)

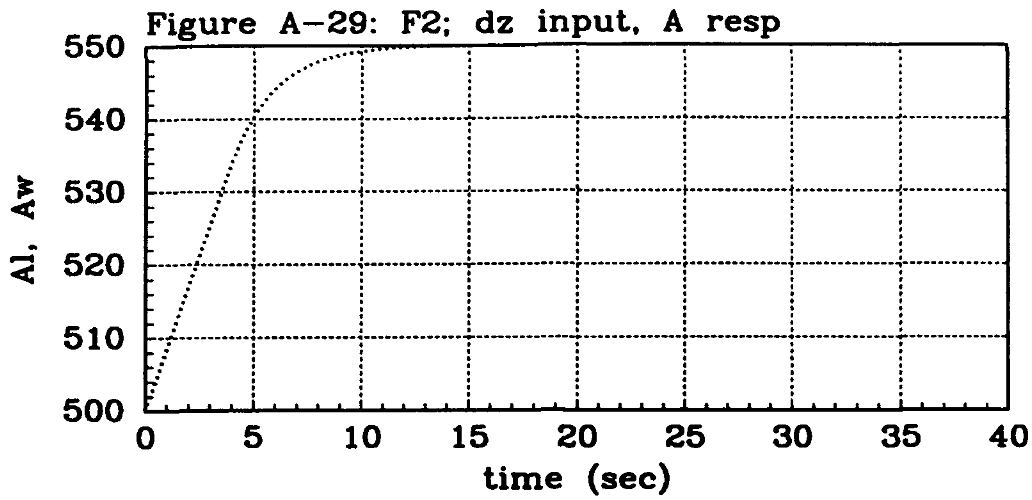


Figure A-29: F2; dz input, A resp
Al, Aw
550
540
530
520
510
500
0
5
10
15
20
25
30
35
40
time (sec)

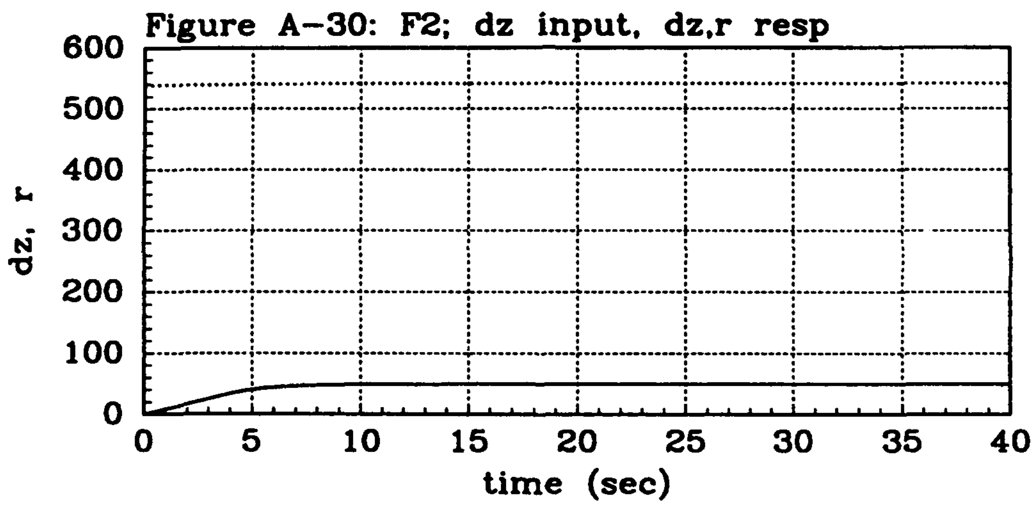


Figure A-30: F2; dz input, dz,r resp
dz, r
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
time (sec)

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Continuous Super-Block	Ext.Inputs	Ext.Outputs
f3	9	21

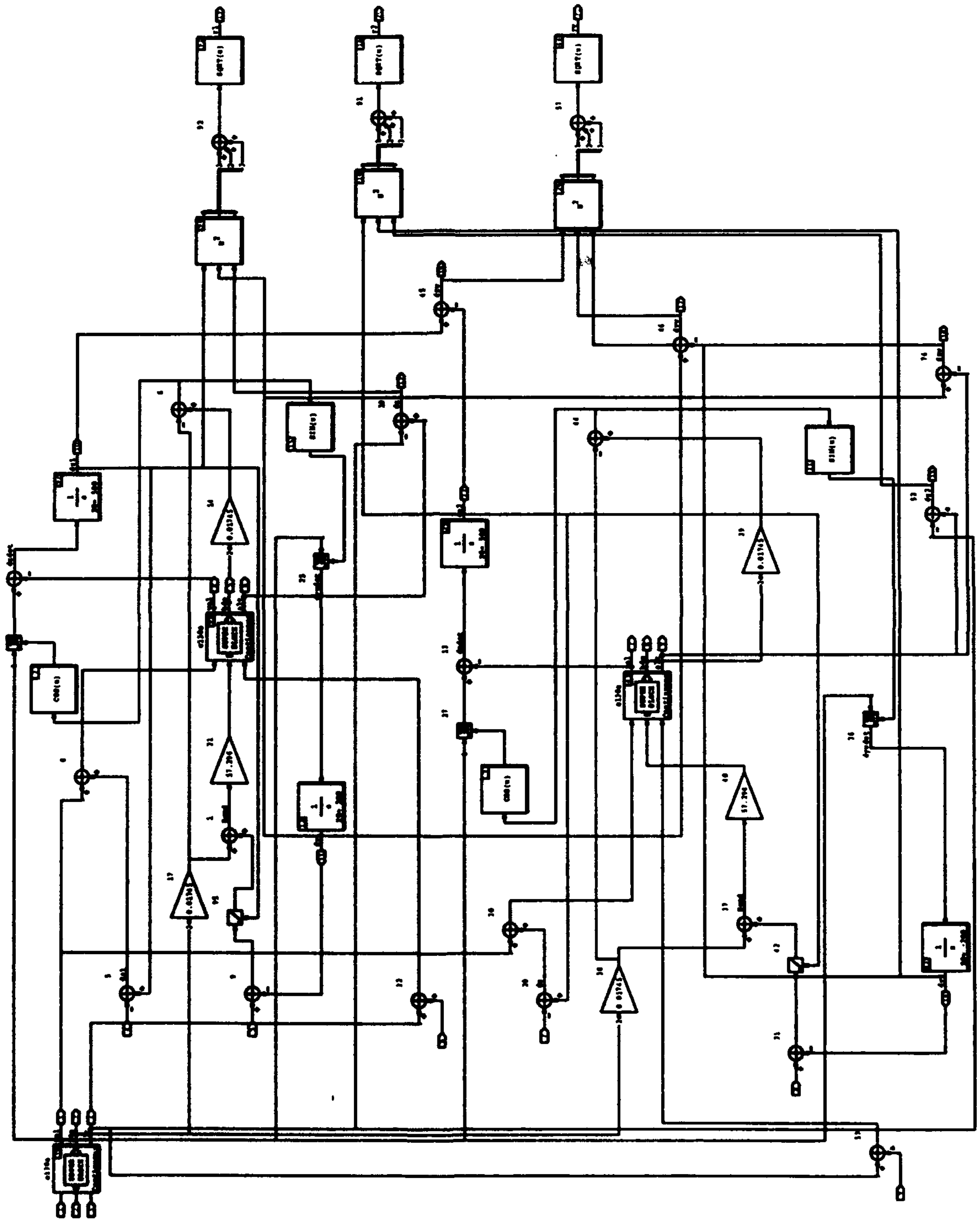


Figure A-31: Basic 3 Ship Formation Model

Figure A-32: F3; V input, V resp

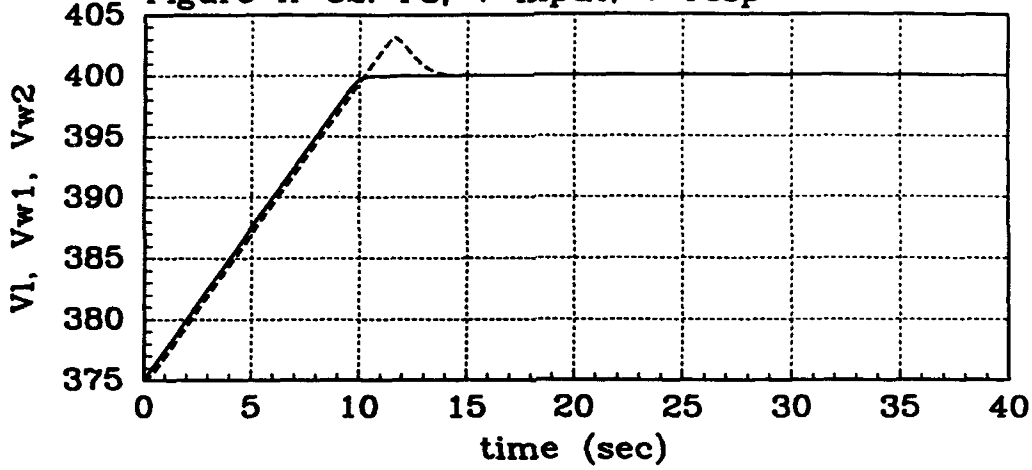


Figure A-33: F3; V input, dx resp

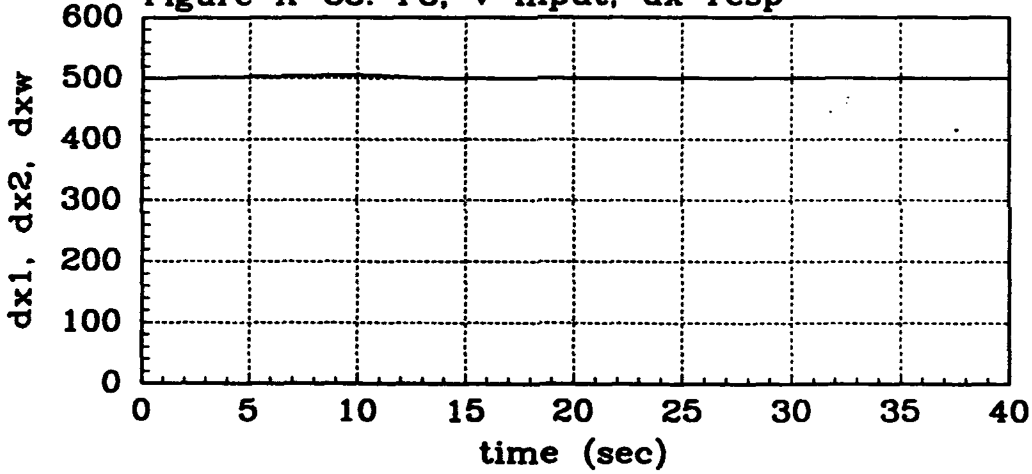


Figure A-34: F3; V input, r resp

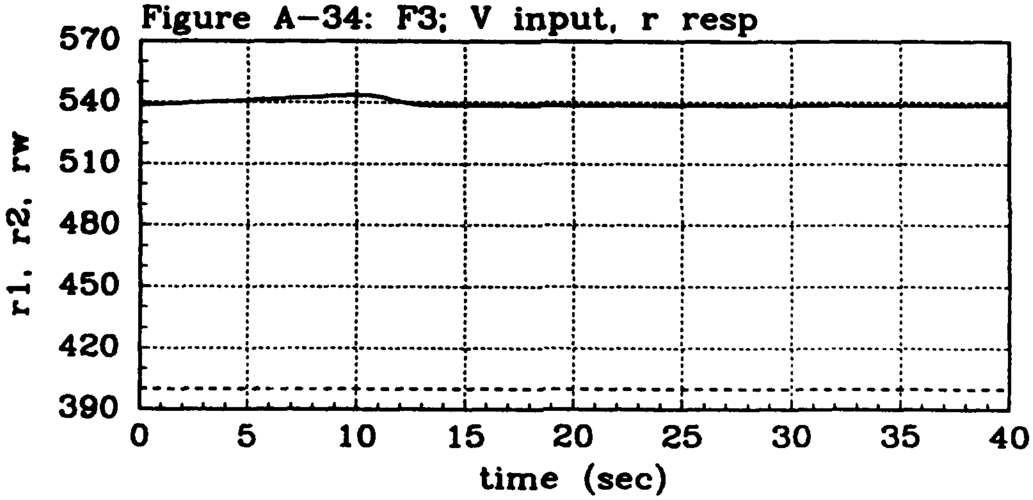


Figure A-35: F3; dx1,2 input, V resp

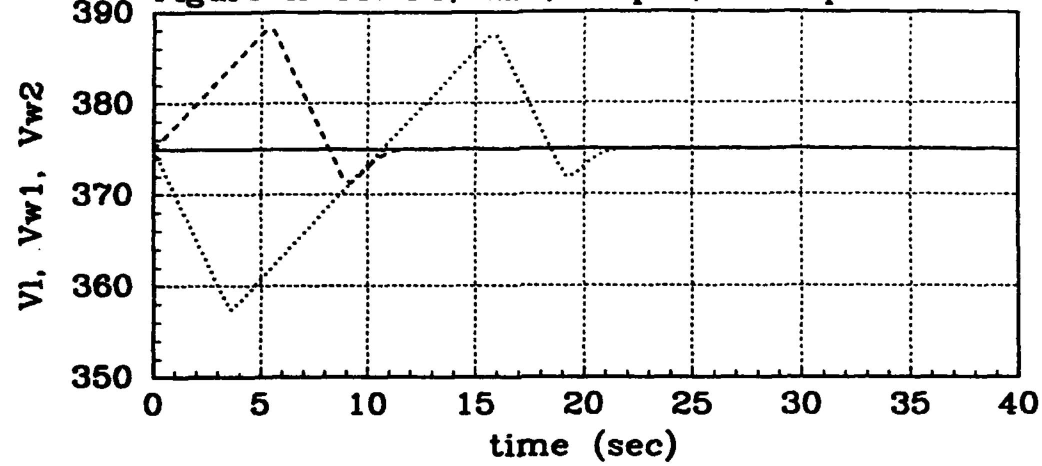


Figure A-36: F3; dx1,2 input, dx resp

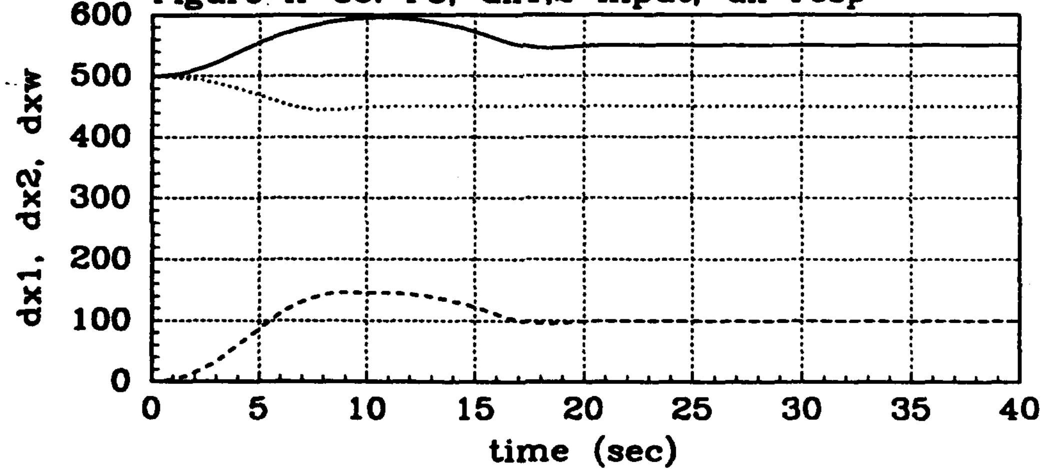


Figure A-37: F3; dx1,2 input, r resp

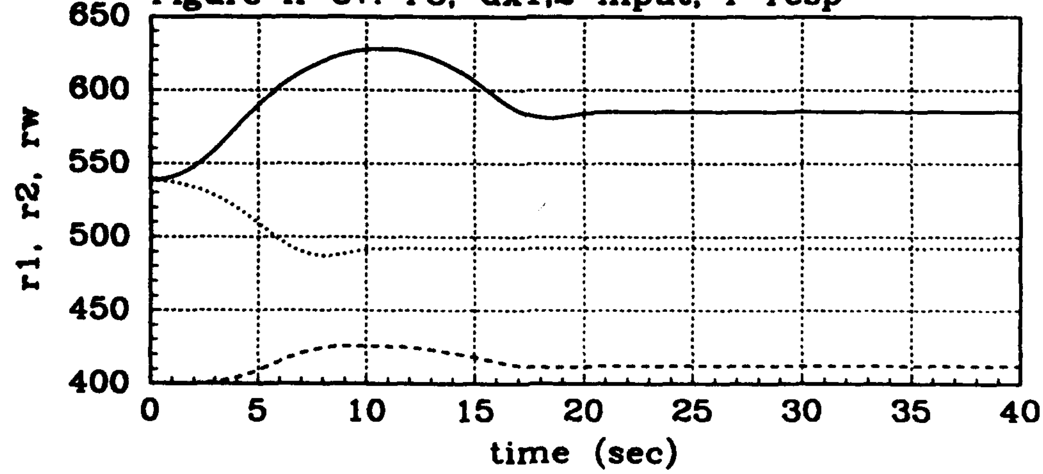


Figure A-38: F3; H input, H resp

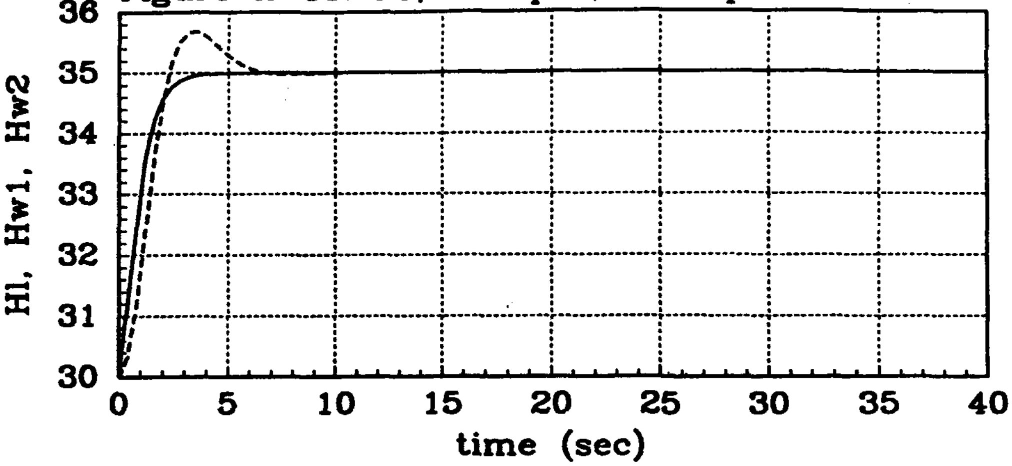


Figure A-39: F3; H input, dy resp

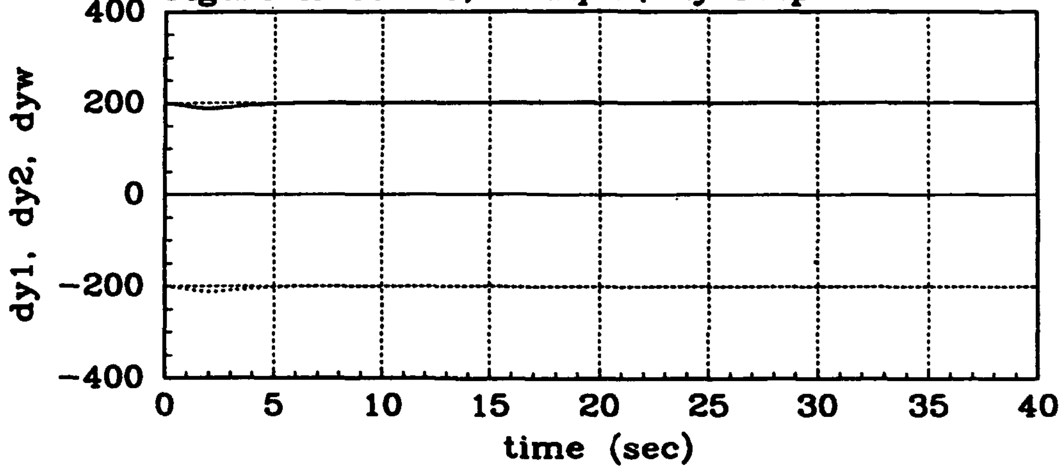


Figure A-40: F3; H input, r resp

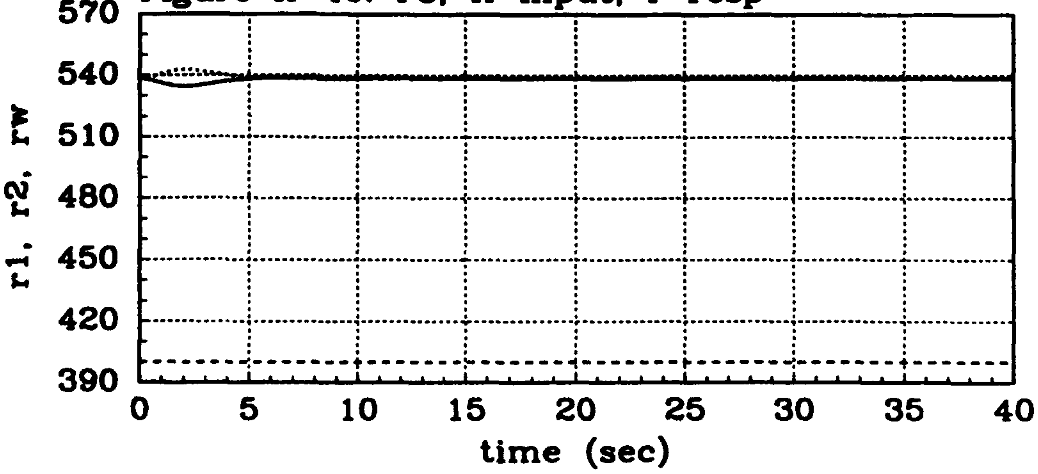


Figure A-41: F3; dy1,2 input, H resp

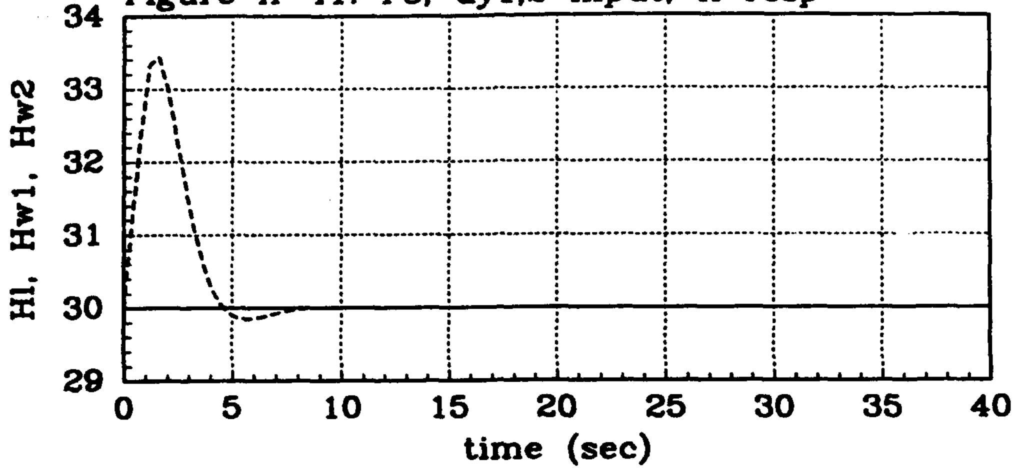


Figure A-42: F3; dy1,2 input, dy resp

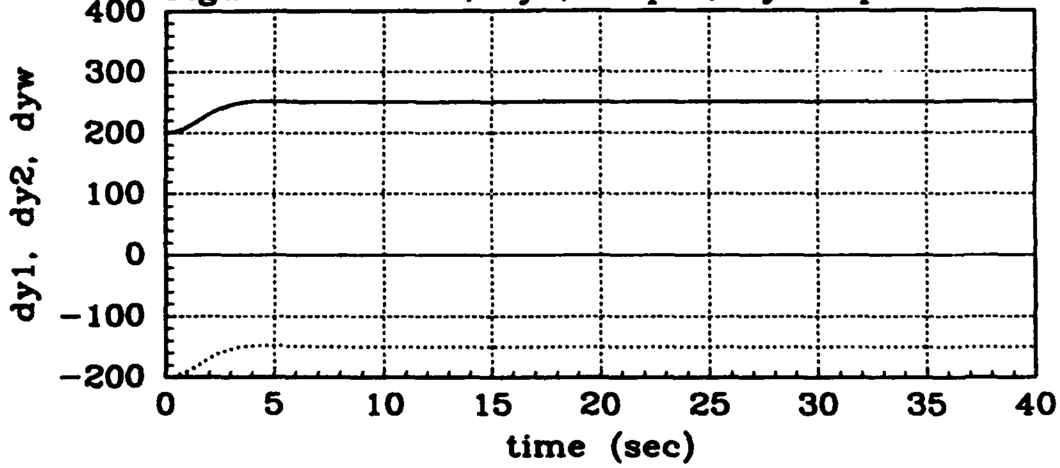


Figure A-43: F3; dy1,2 input, r resp

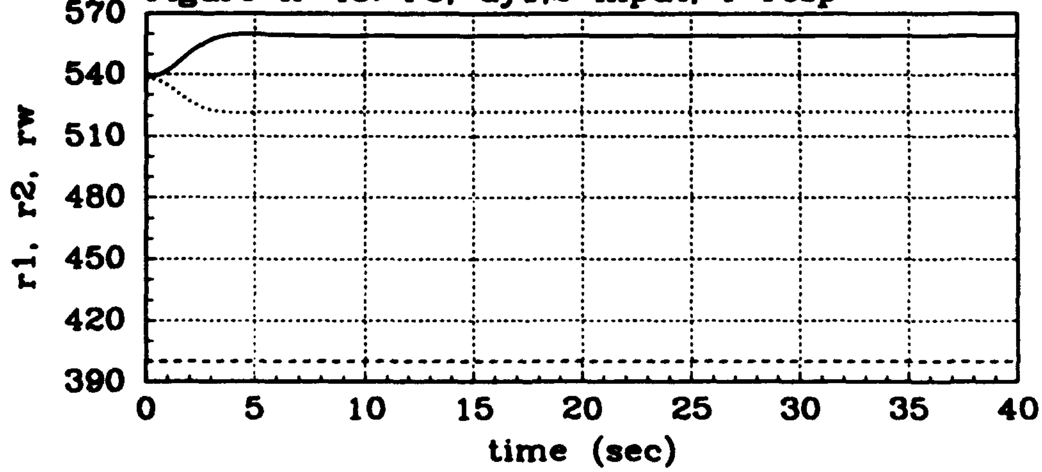


Figure A-44: F3; A input, A resp

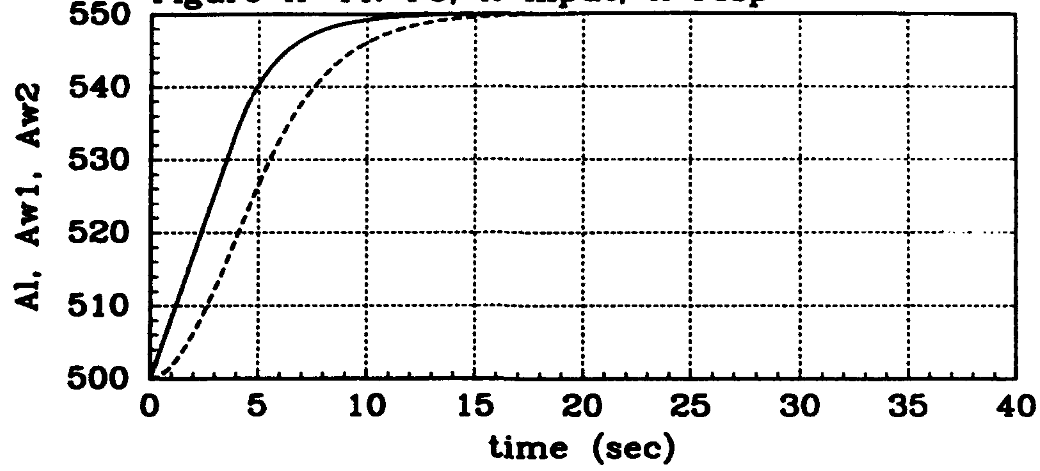


Figure A-45: F3; A input, dz resp

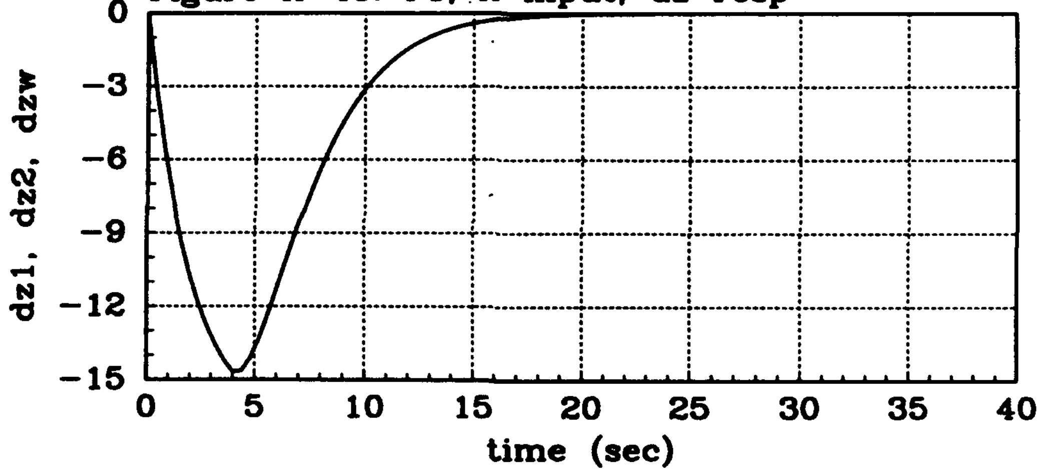


Figure A-46: F3; A input, r resp

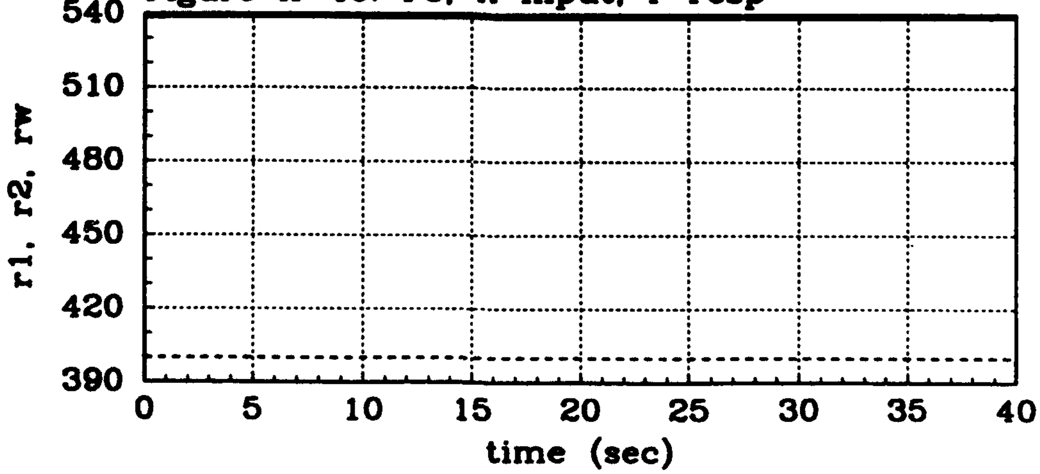


Figure A-47: F3; dz1,2 input, A resp

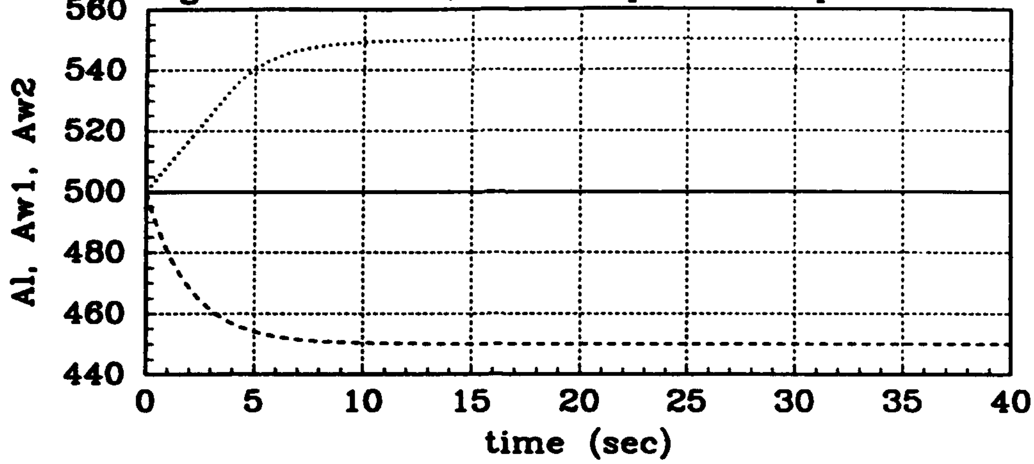


Figure A-48: F3; dz1,2 input, dz resp

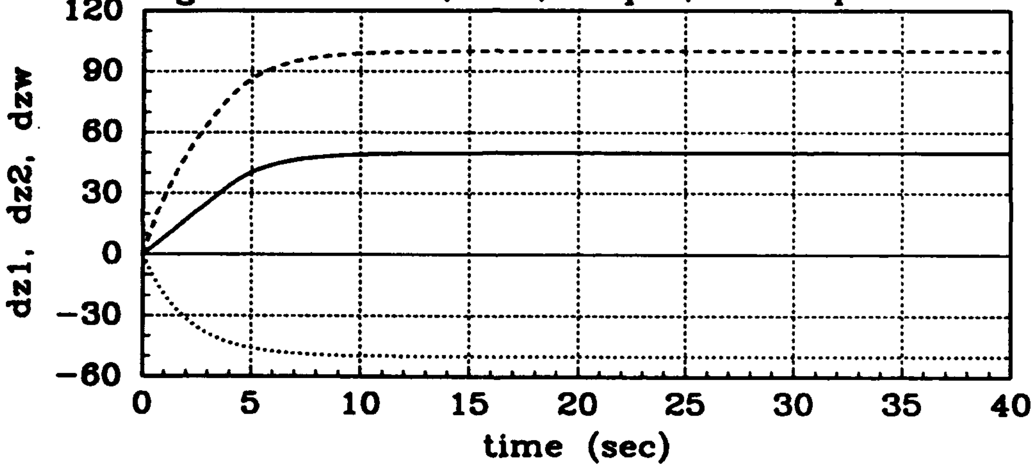
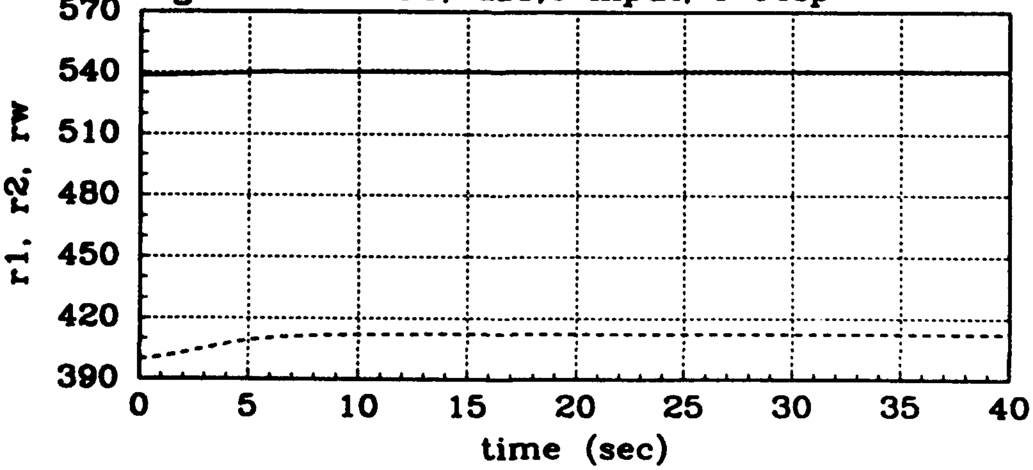


Figure A-49: F3; dz1,2 input, r resp



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Continuous Super-Block f4 | Ext.Inputs 9 | Ext.Outputs 21

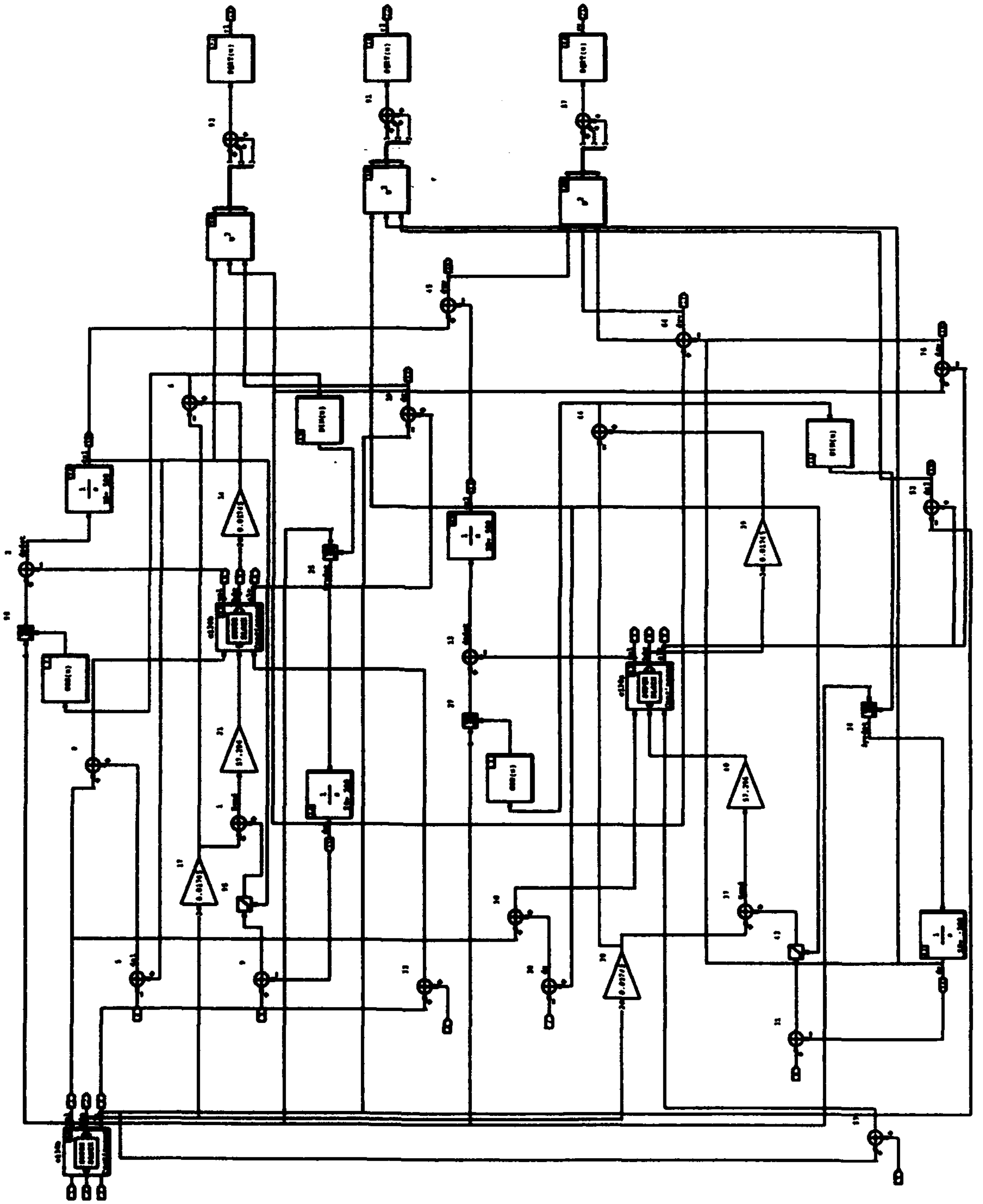


Figure A-50: Basic 3 Ship Mixed Formation Model (F4)

Figure A-51: F4; V input, V resp

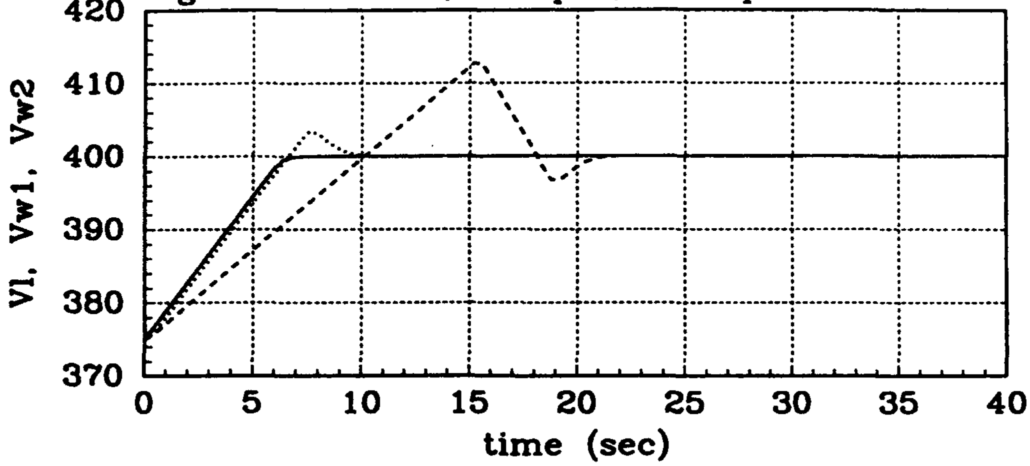


Figure A-52: F4; V input, dx resp

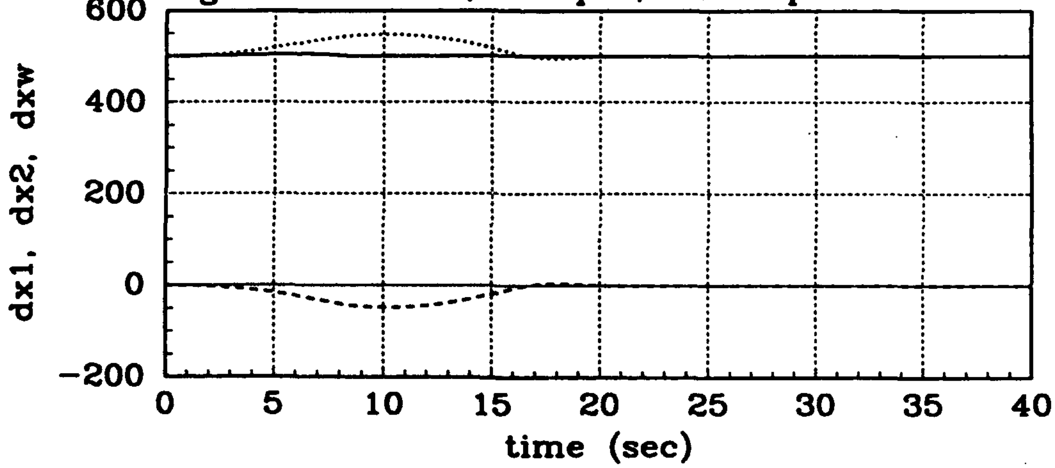


Figure A-53: F4; V input, r resp

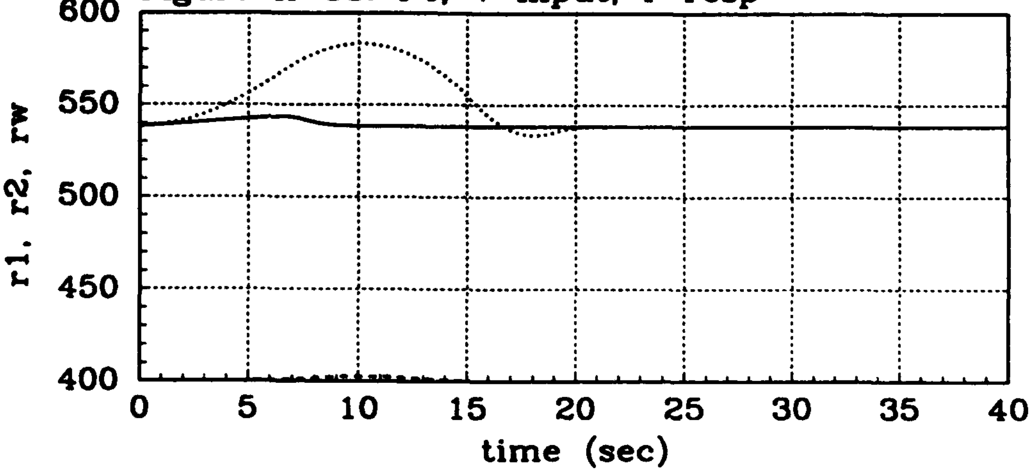


Figure A-54: F4; dx1,2 input, V resp

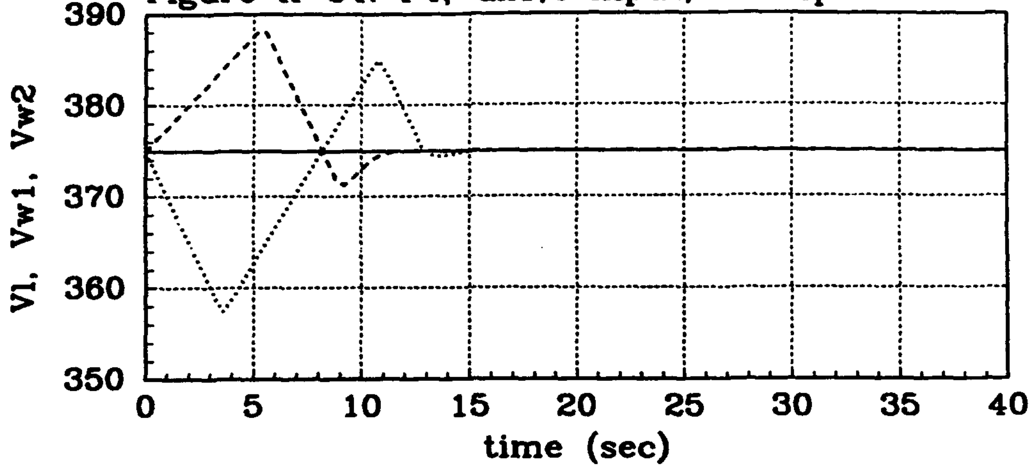


Figure A-55: F4; dx1,2 input, dx resp

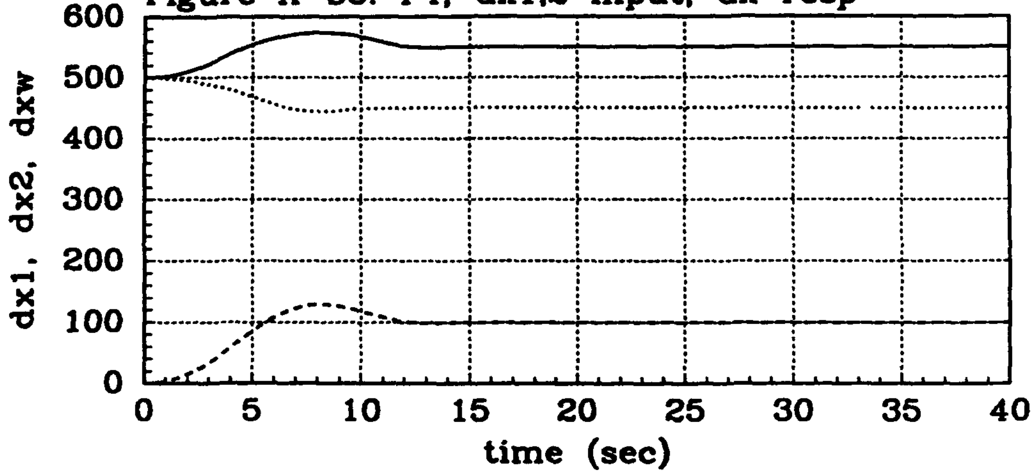
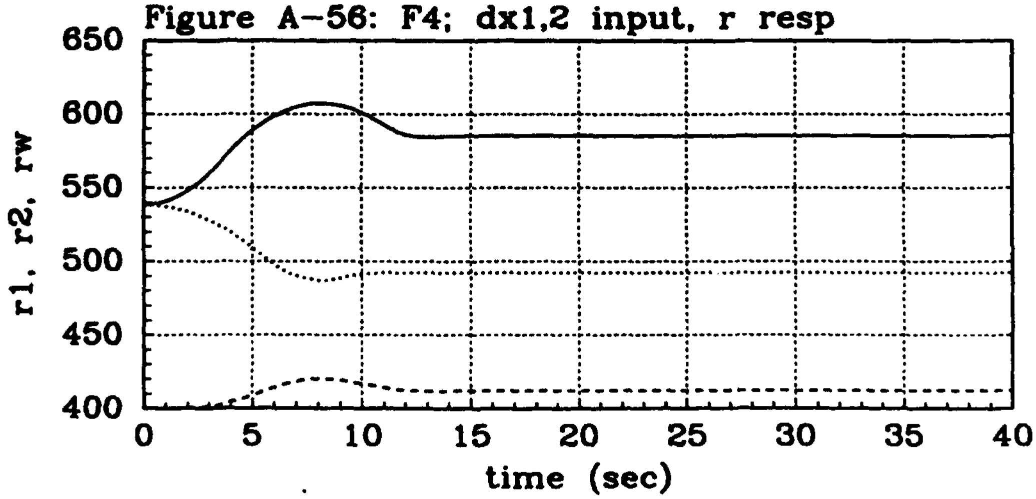


Figure A-56: F4; dx1,2 input, r resp



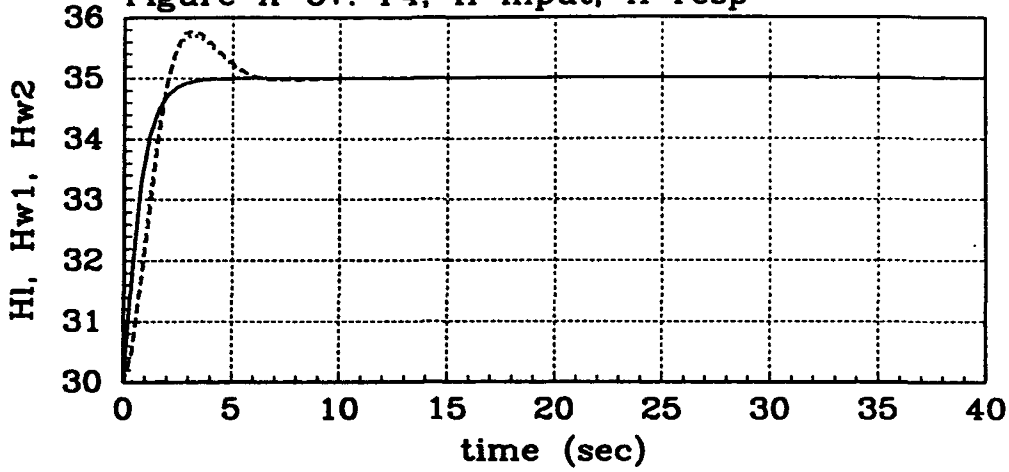


Figure A-57: F4; H input, H resp

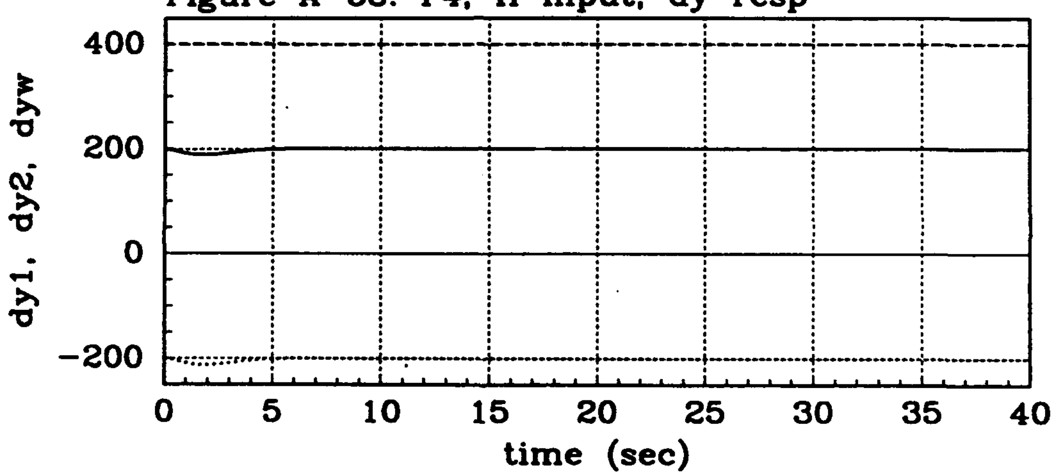


Figure A-58: F4; H input, dy resp

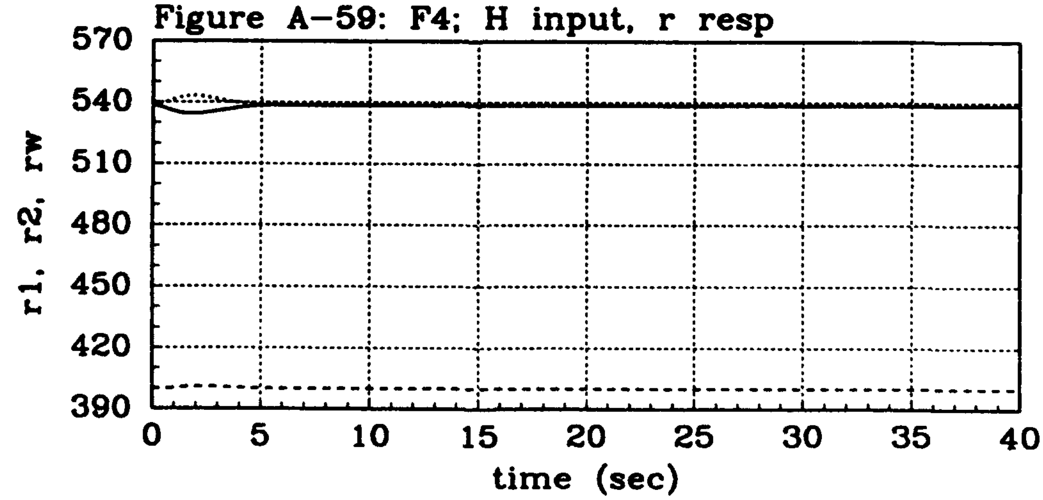


Figure A-59: F4; H input, r resp

Figure A-60: F4; dy1,2 input, H resp

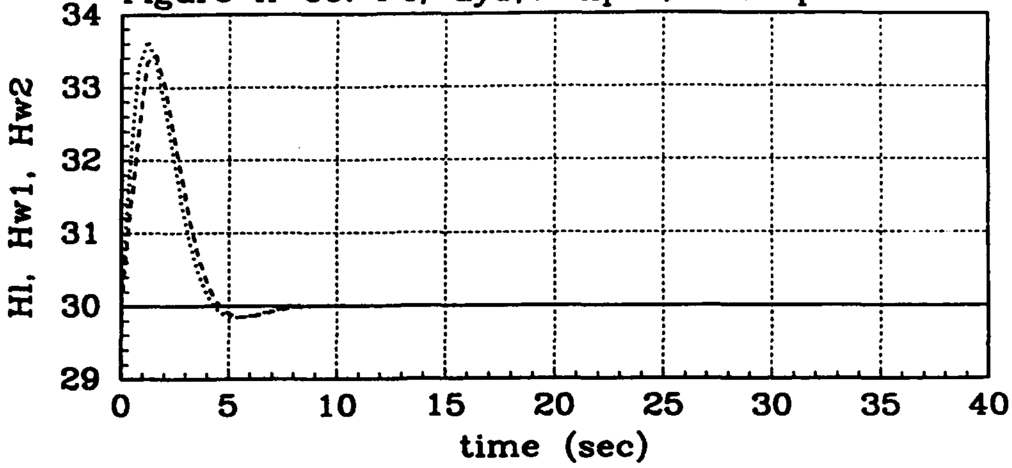


Figure A-61: F4; dy1,2 input, dy resp

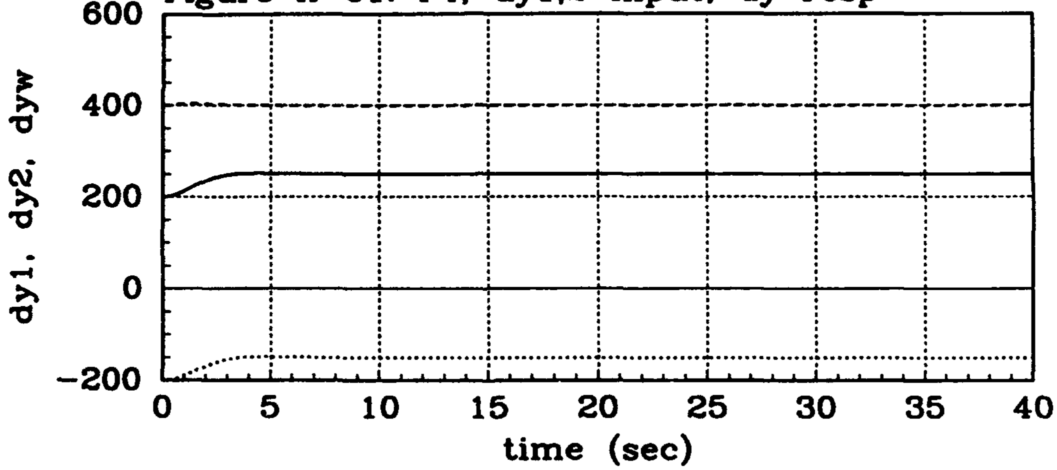


Figure A-62: F4; dy1,2 input, r resp

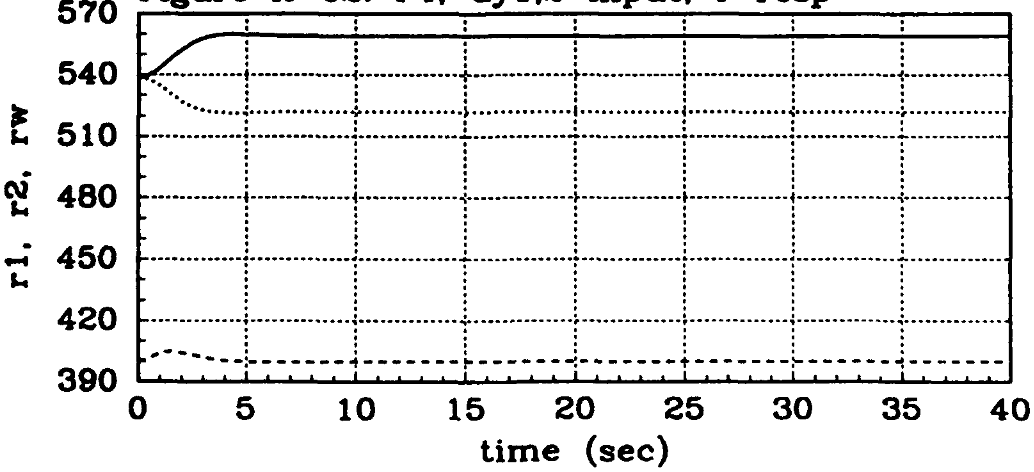


Figure A-63: F4; A input, A resp

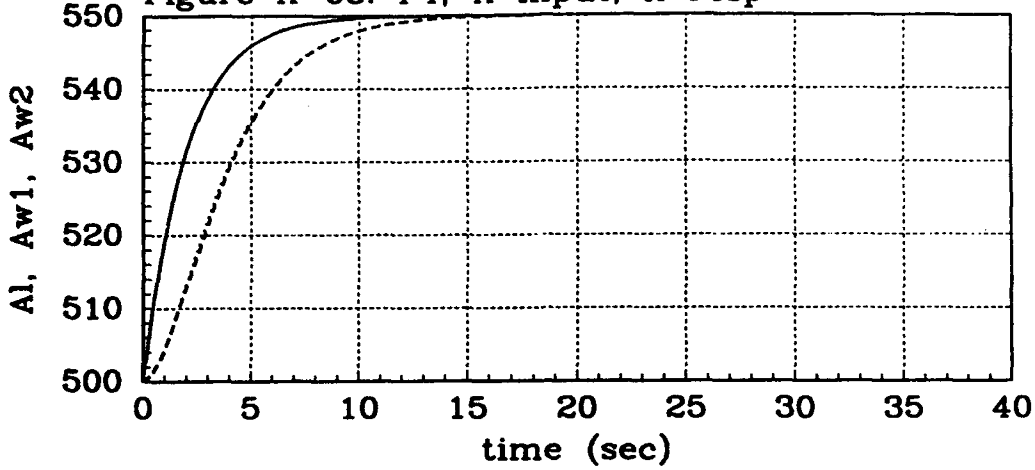


Figure A-64: F4; A input, dz resp

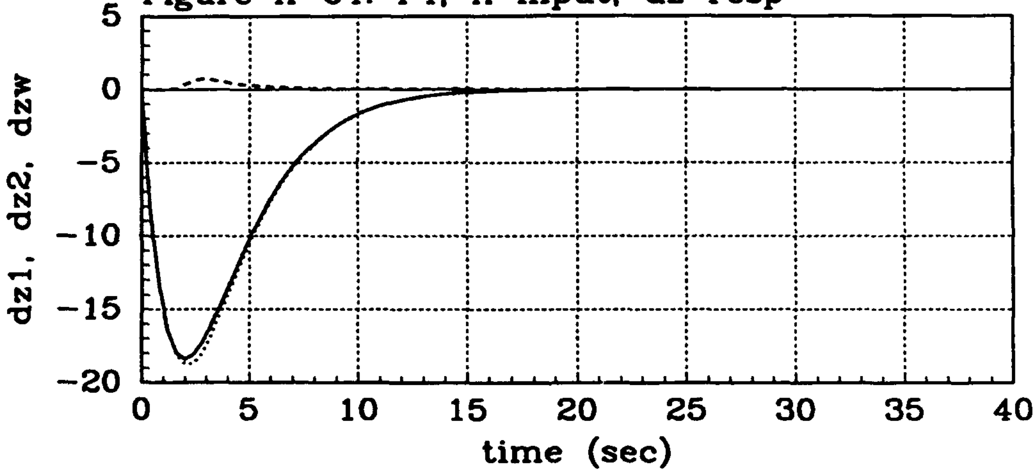


Figure A-65: F4; A input, r resp

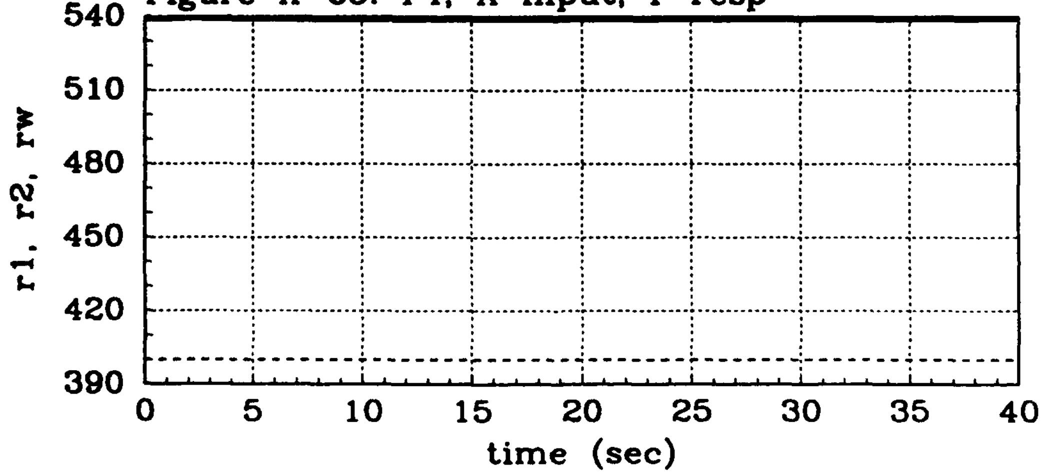


Figure A-66: F4; dz1,2 input, A resp

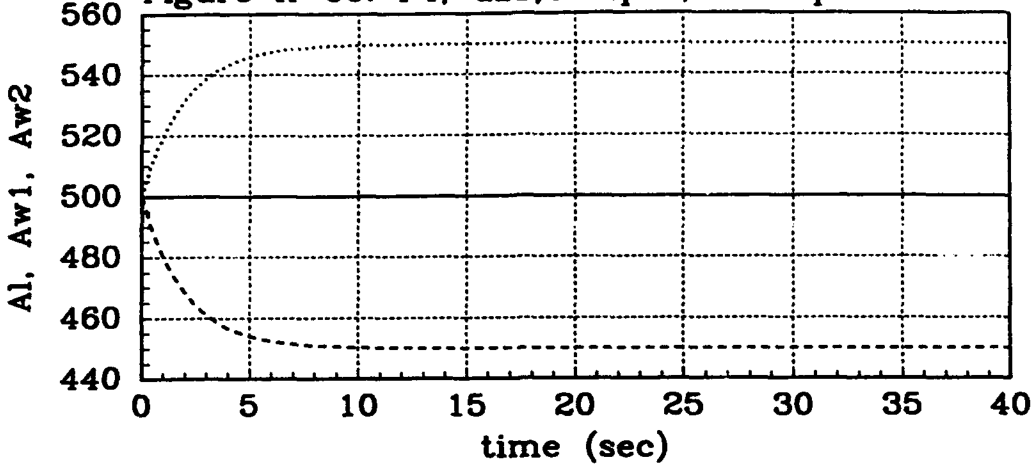


Figure A-67: F4; dz1,2 input, dz resp

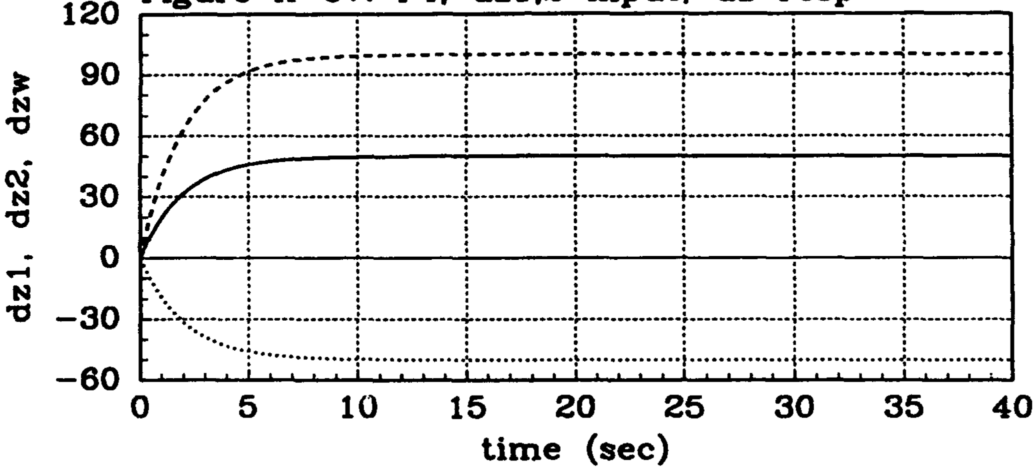
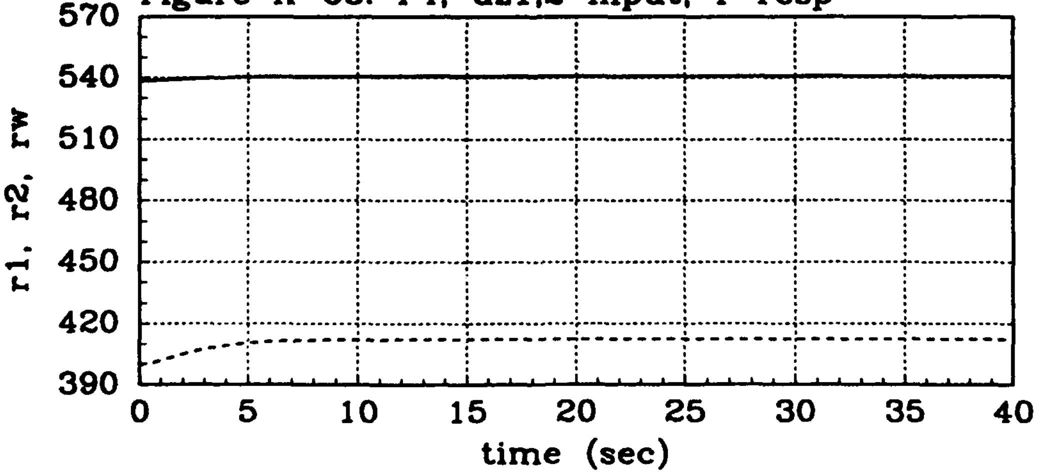


Figure A-68: F4; dz1,2 input, r resp



Appendix B: Controlled Formation System Responses

This appendix contains plots depicting the performance of the complete, controlled formation control system. The formation model used for all plots has a lead and wing #1 aircraft of similar capabilities, and a wing #2 which is a less capable aircraft in terms of maneuvering capabilities (F4 in the report). Complete system evaluation responses are contained here which can be compared with those of the open loop, or uncontrolled models shown in Appendix A. The plots contained in this appendix are arranged as follows.

Legend For All Plots

1st parameter	:	Solid Line (---------)
2nd parameter	:	Dotted Line (·············)
3rd parameter	:	Dashed Line (- - - -)

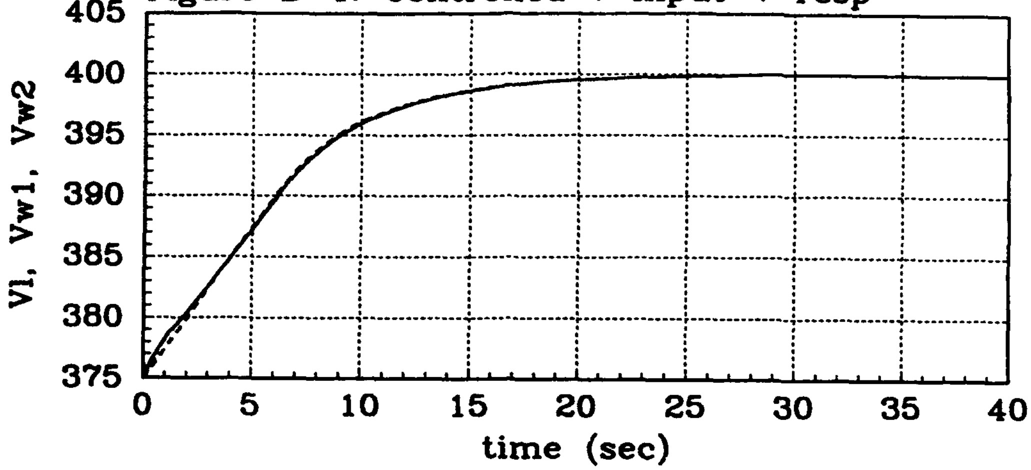


Figure B-1: Controlled V input-V resp

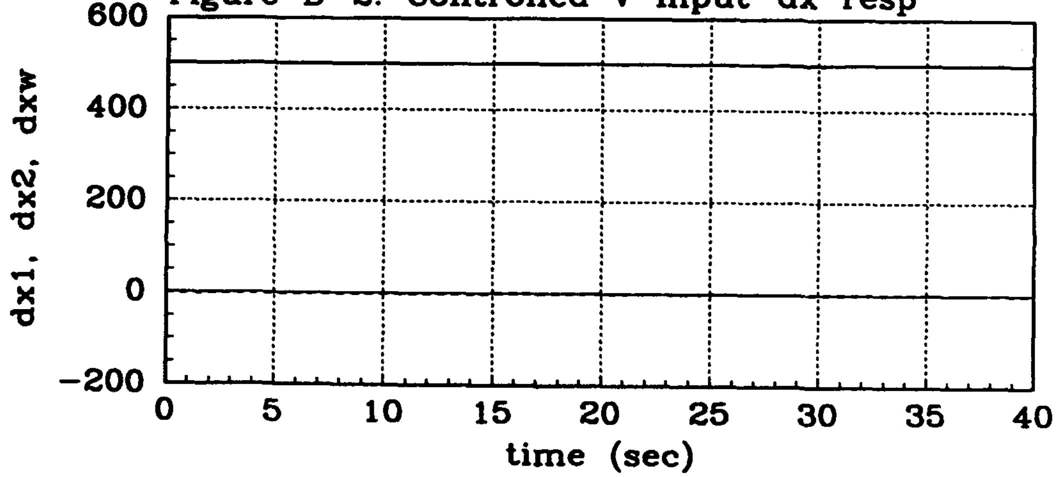


Figure B-2: Controlled V input-dx resp

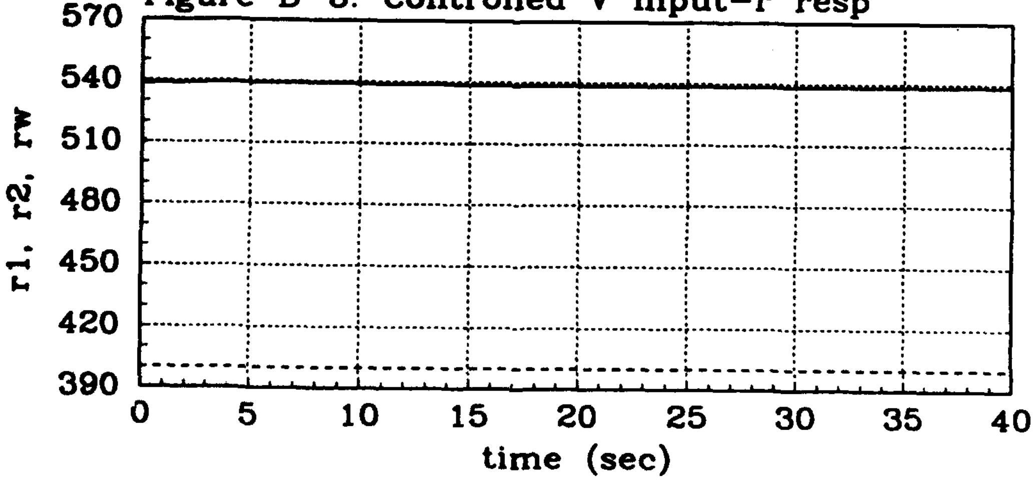


Figure B-3: Controlled V input-r resp

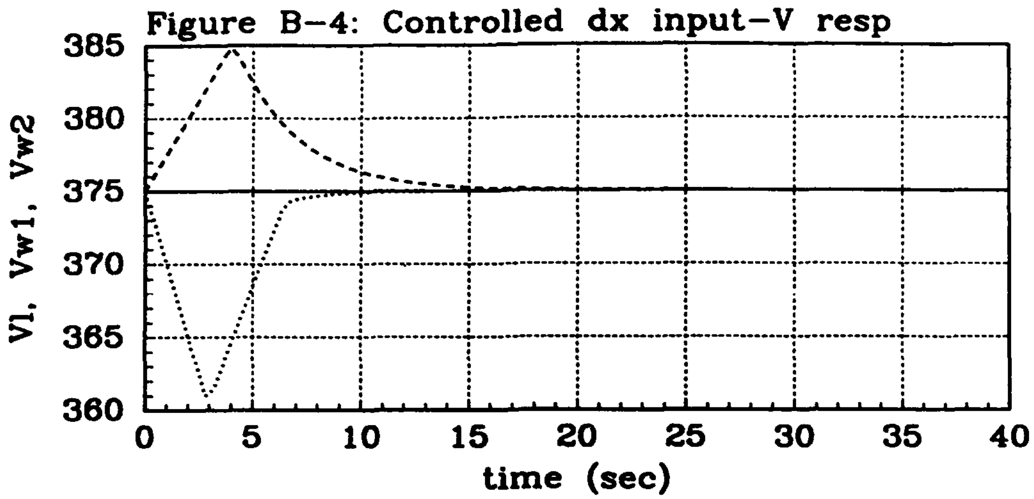


Figure B-4: Controlled dx input-V resp
Vl, Vw1, Vw2
385
380
375
370
365
360
0
5
10
15
20
25
30
35
40
time (sec)

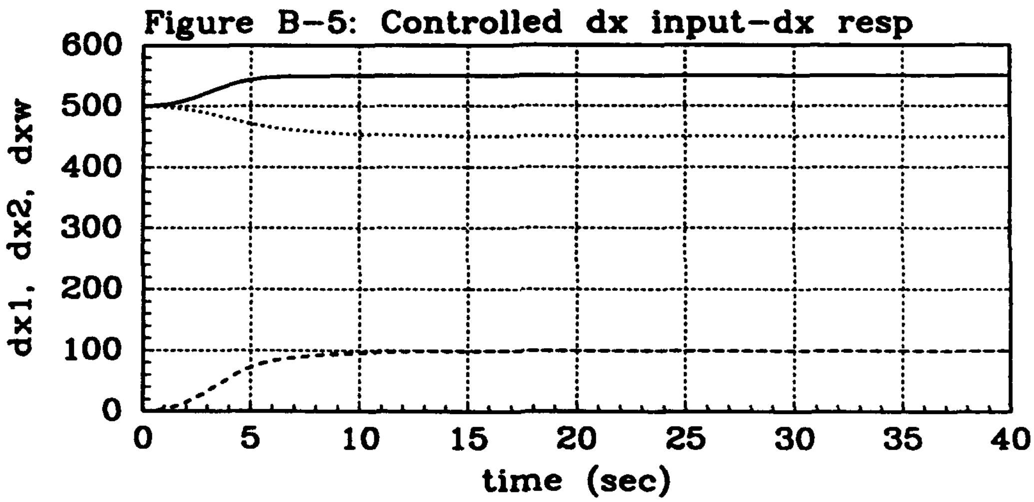


Figure B-5: Controlled dx input-dx resp
dx1, dx2, dxw
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
time (sec)

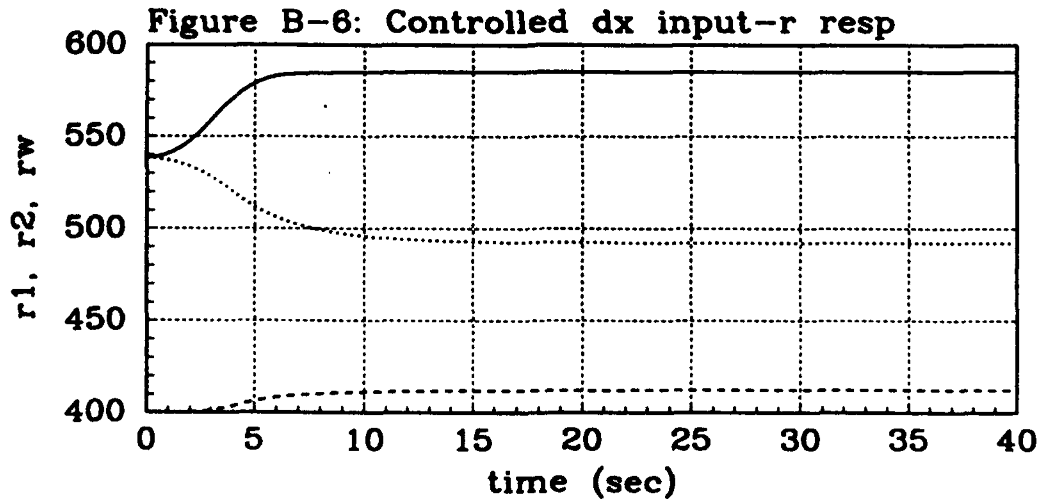


Figure B-6: Controlled dx input-r resp
r1, r2, rw
600
550
500
450
400
0
5
10
15
20
25
30
35
40
time (sec)

Figure B-7: Controlled H input-H resp

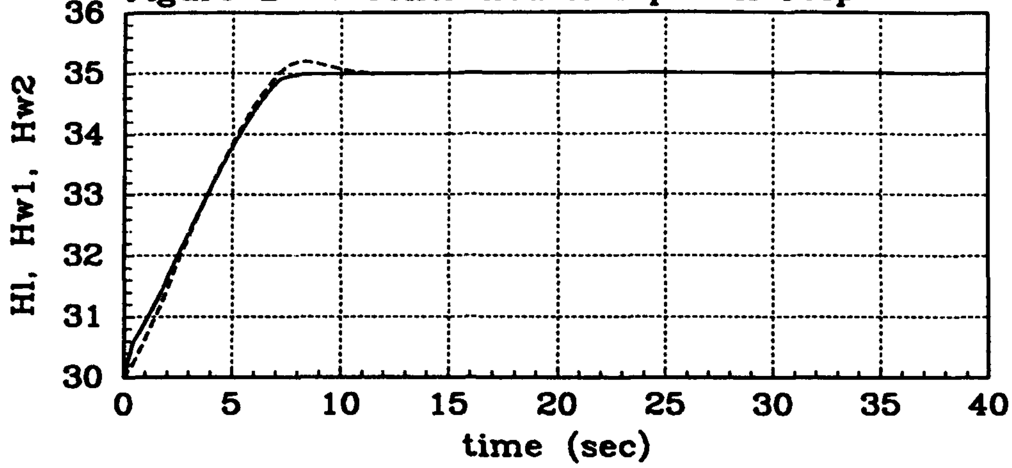


Figure B-8: Controlled H input-dy resp

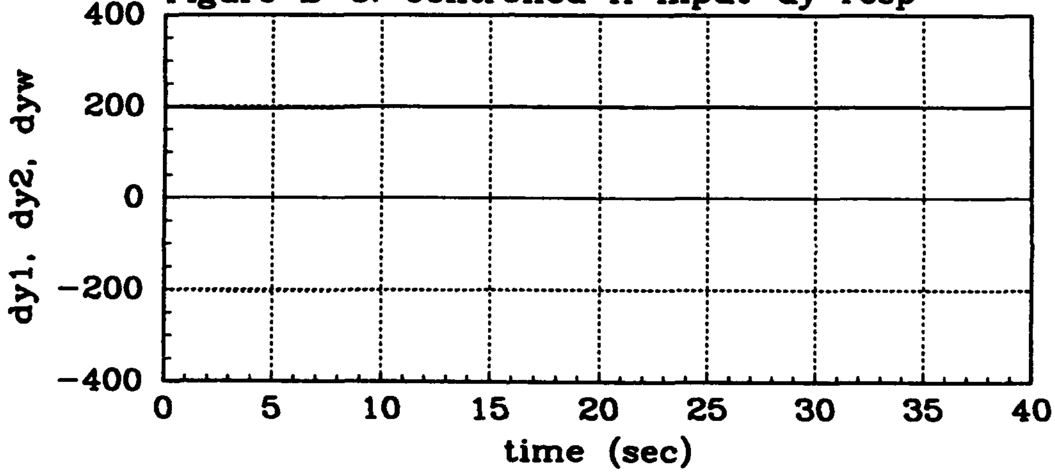
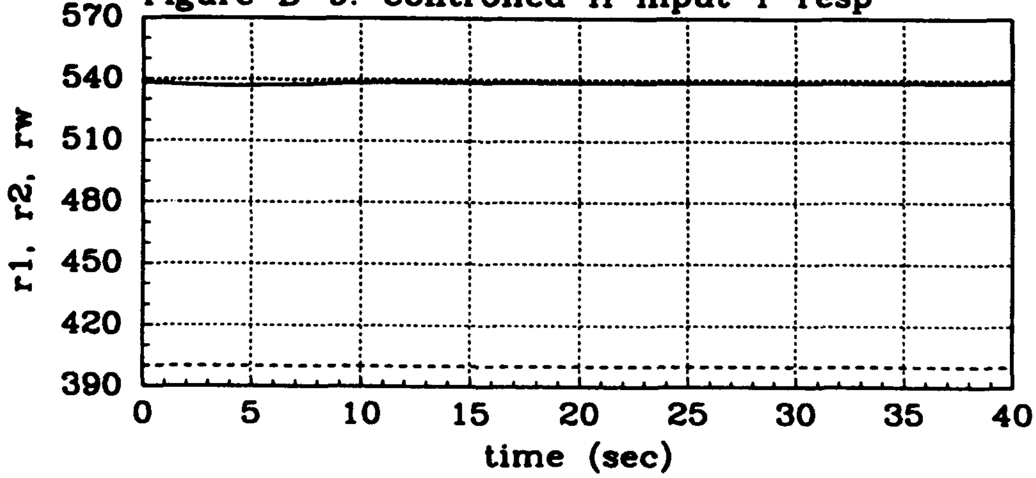


Figure B-9: Controlled H input-r resp



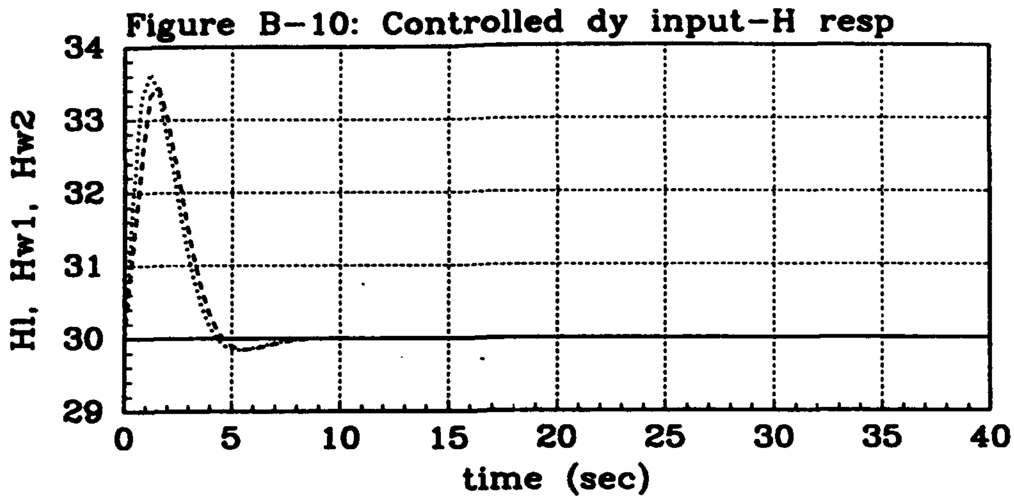


Figure B-10: Controlled dy input-H resp
34
33
32
31
30
29
Hl, Hw1, Hw2
0
5
10
15
20
25
30
35
40
time (sec)

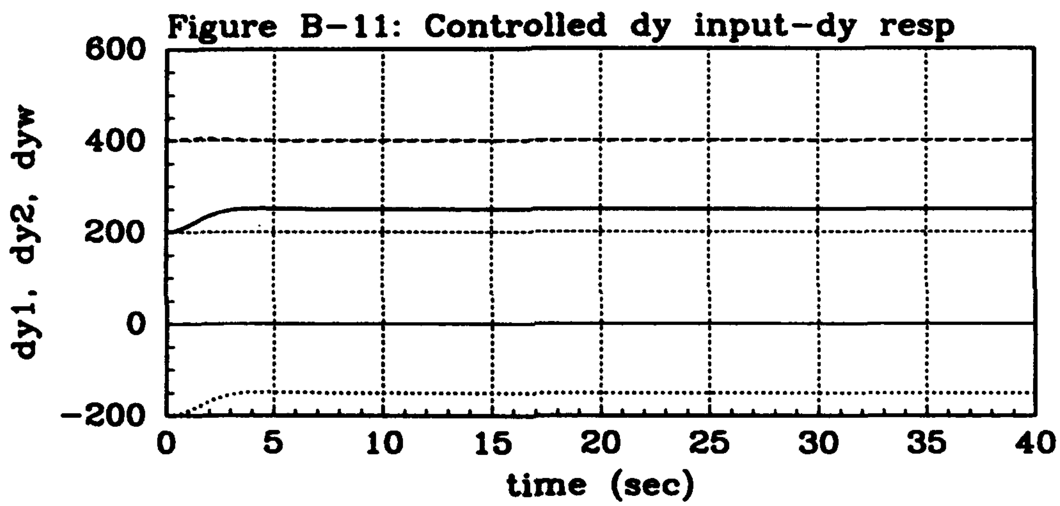


Figure B-11: Controlled dy input-dy resp
600
400
200
0
-200
dy1, dy2, dyw
0
5
10
15
20
25
30
35
40
time (sec)

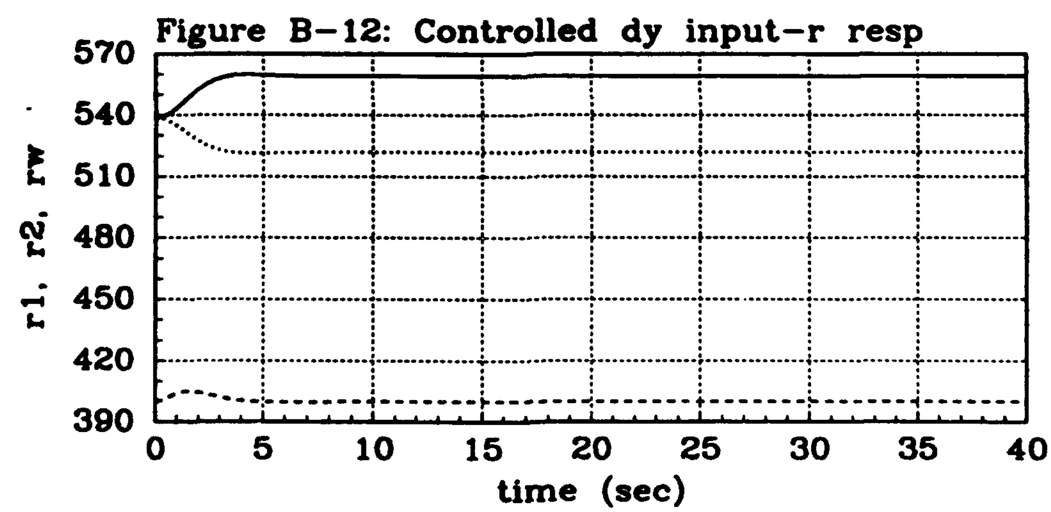


Figure B-12: Controlled dy input-r resp
570
540
510
480
450
420
390
r1, r2, rw
0
5
10
15
20
25
30
35
40
time (sec)

Figure B-13: Controlled A input-A resp

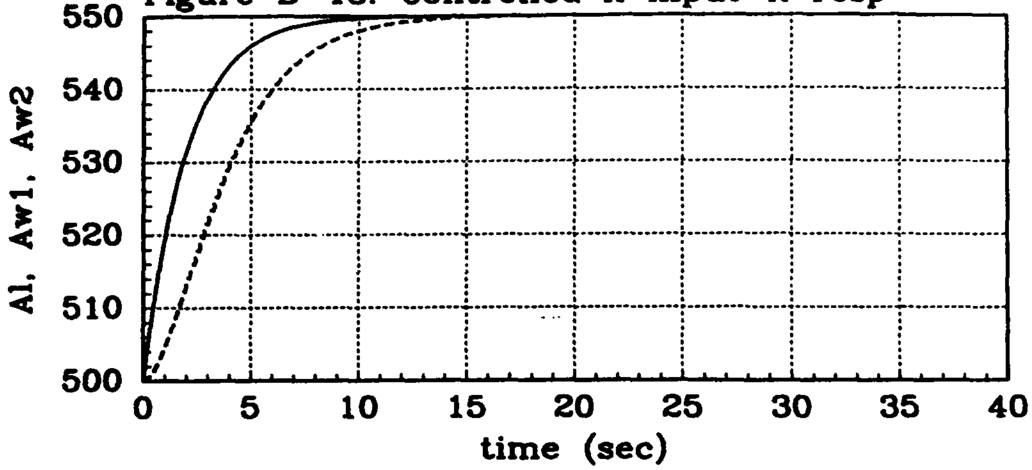


Figure B-14: Controlled A input-dz resp

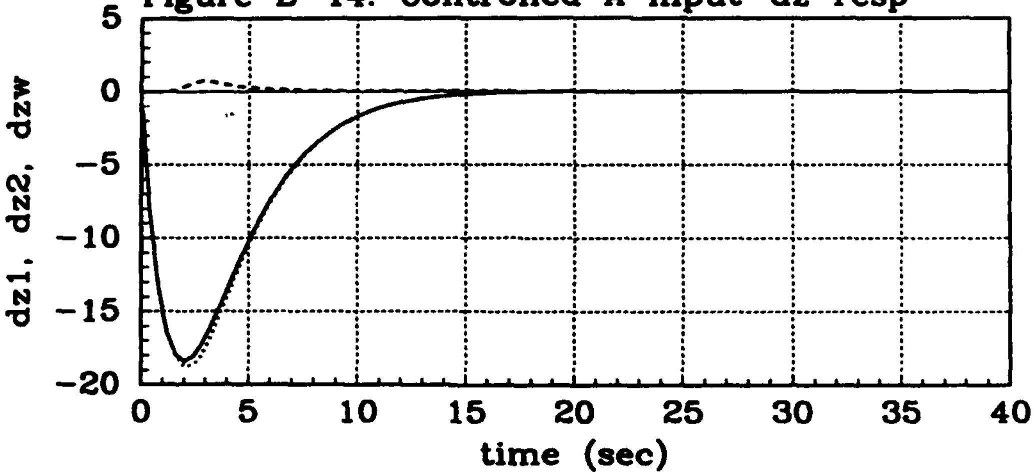


Figure B-15: Controlled A input-r resp

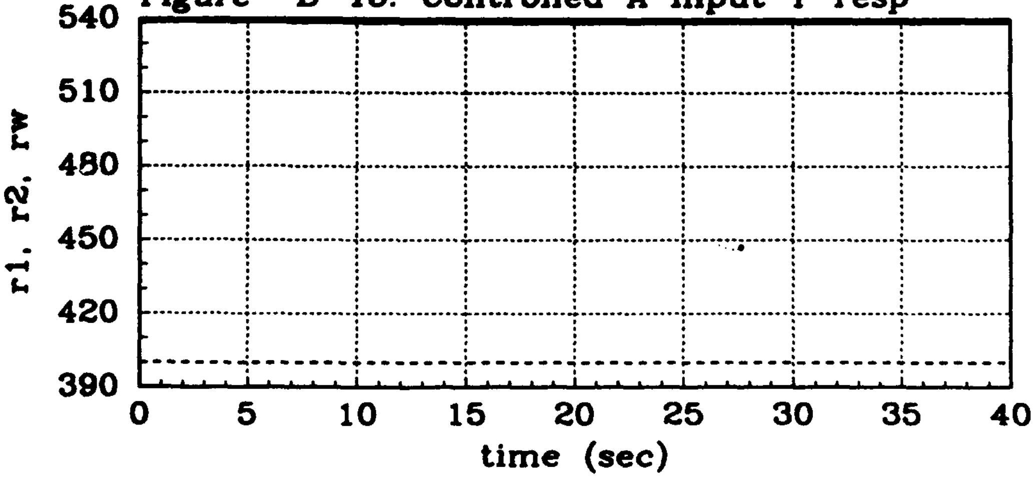


Figure B-16: Controlled dz input-A resp

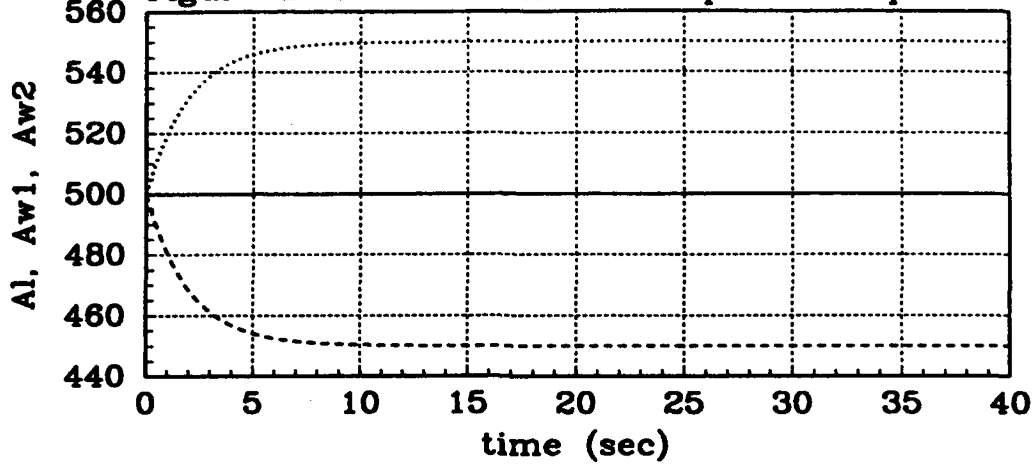


Figure B-17: Controlled dz input-dz resp

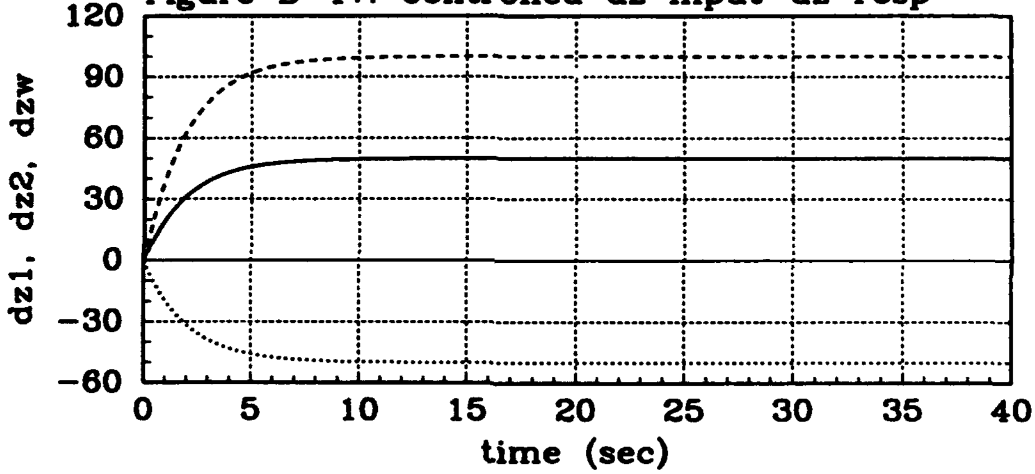


Figure B-18: Controlled dz input-r resp

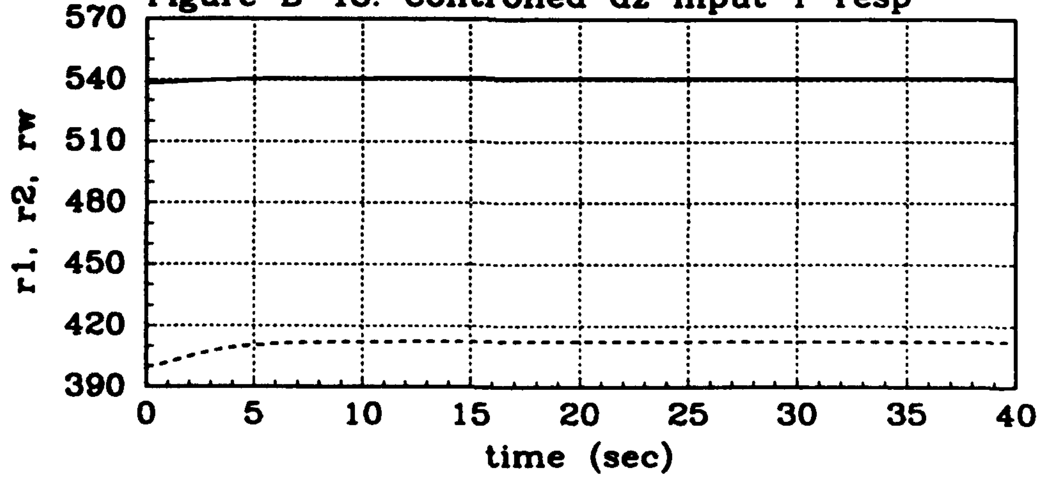


Figure B-19: Flat Turn, V Response

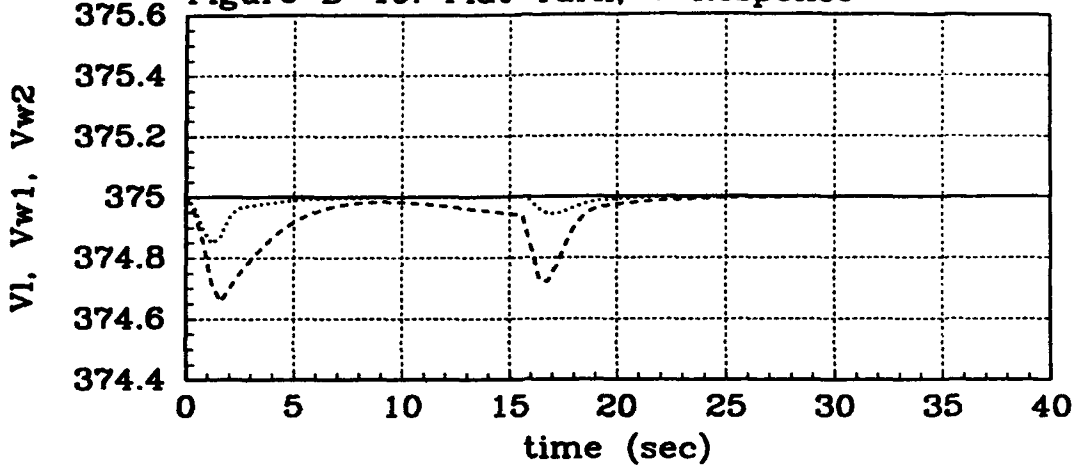


Figure B-20: Flat Turn, dx Response

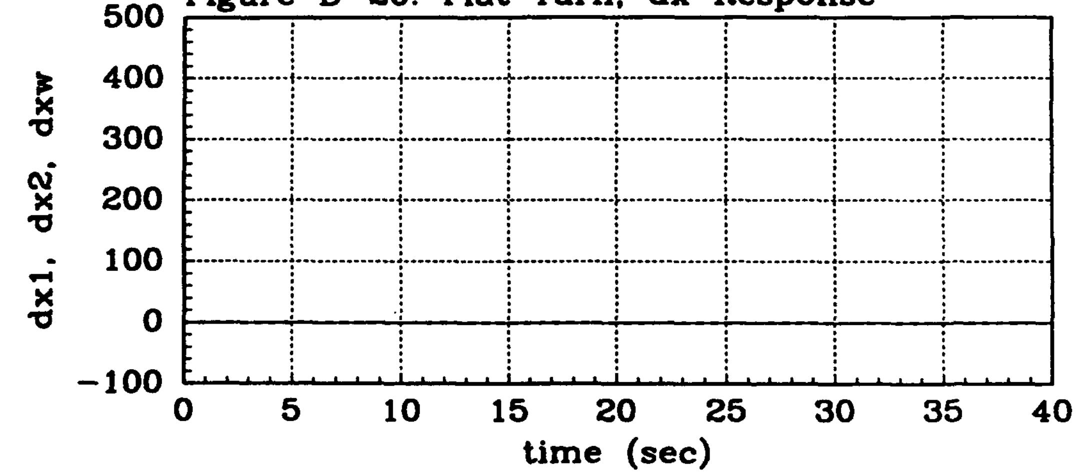


Figure B-21: Flat Turn, H Response

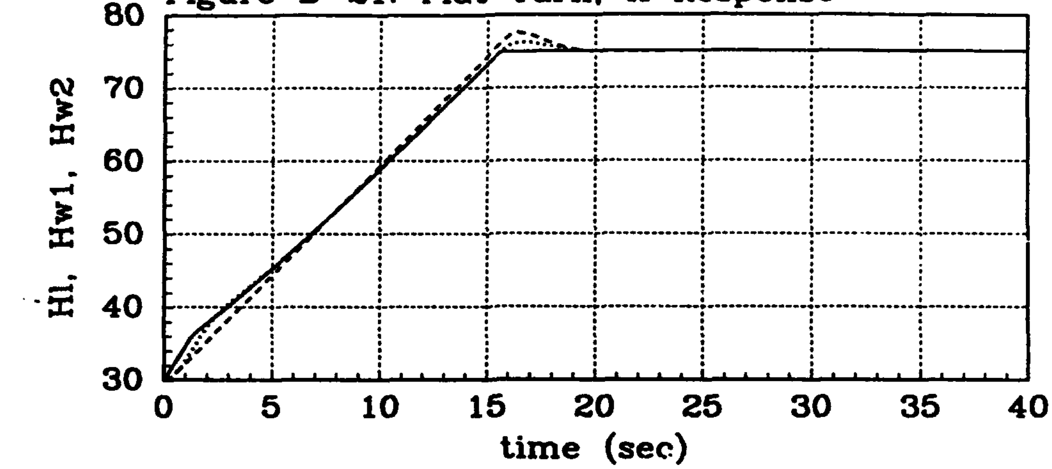


Figure B-22: Flat Turn, dy Response

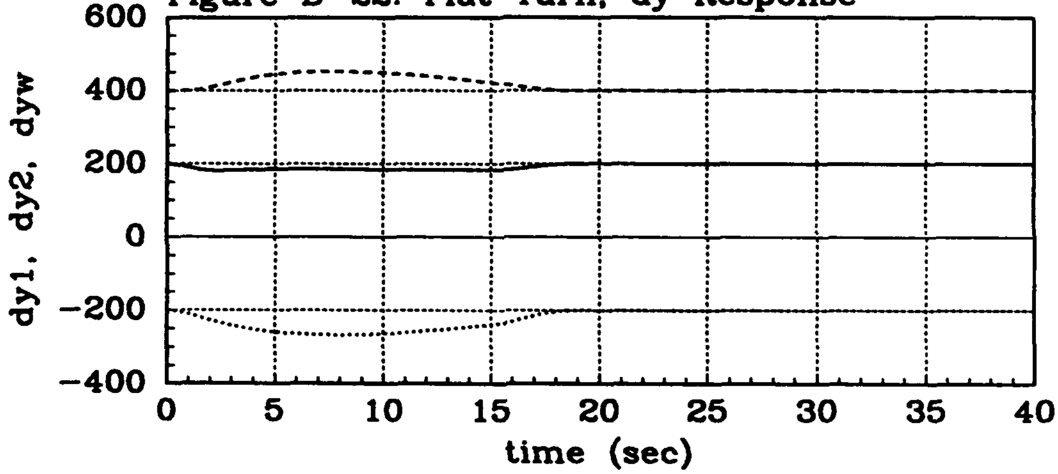
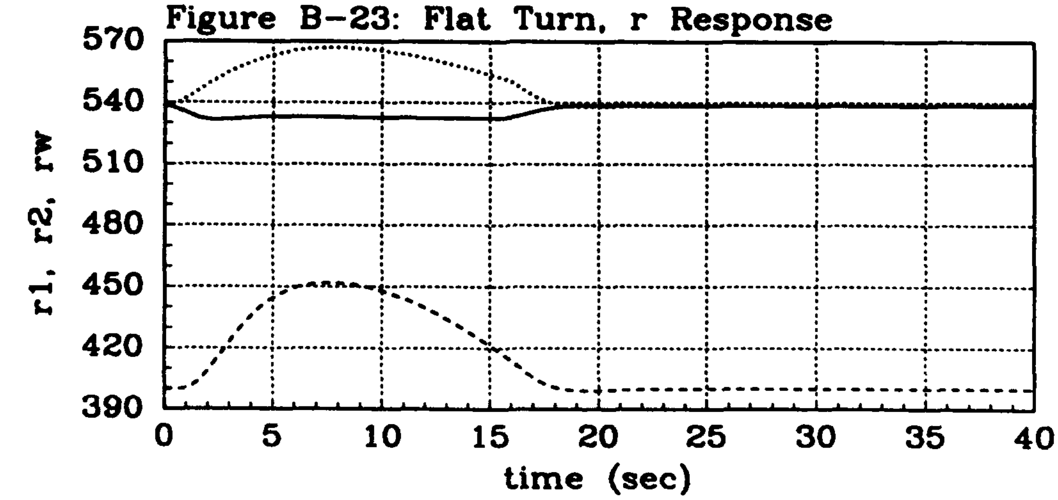


Figure B-23: Flat Turn, r Response



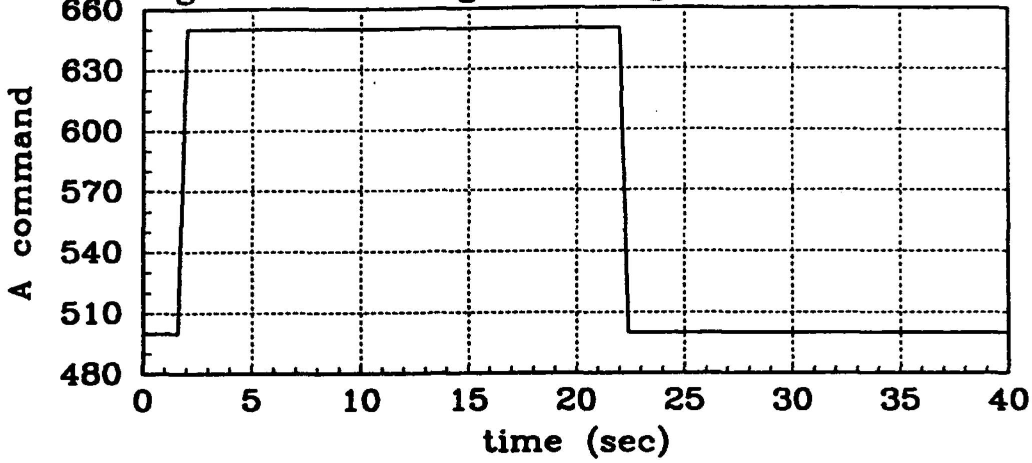


Figure B-24: Ridge Crossing, A Cmnd

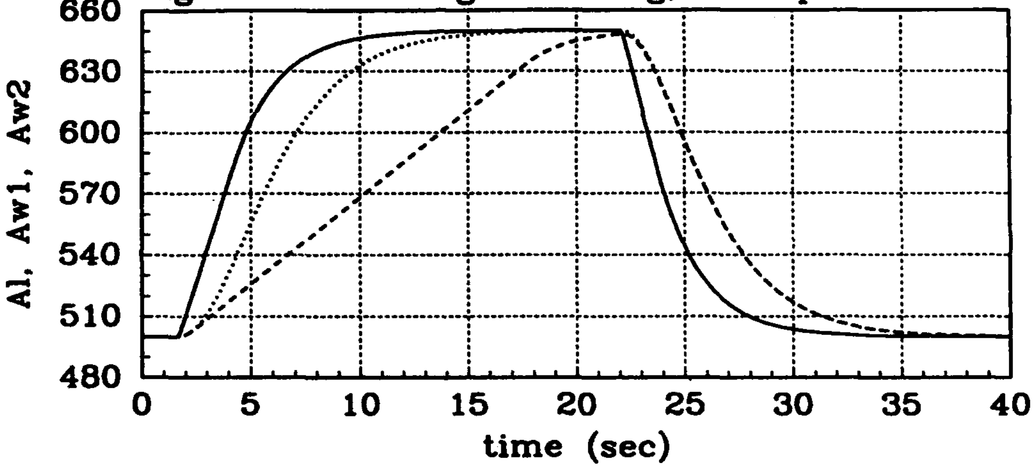


Figure B-25: Ridge Crossing, A resp

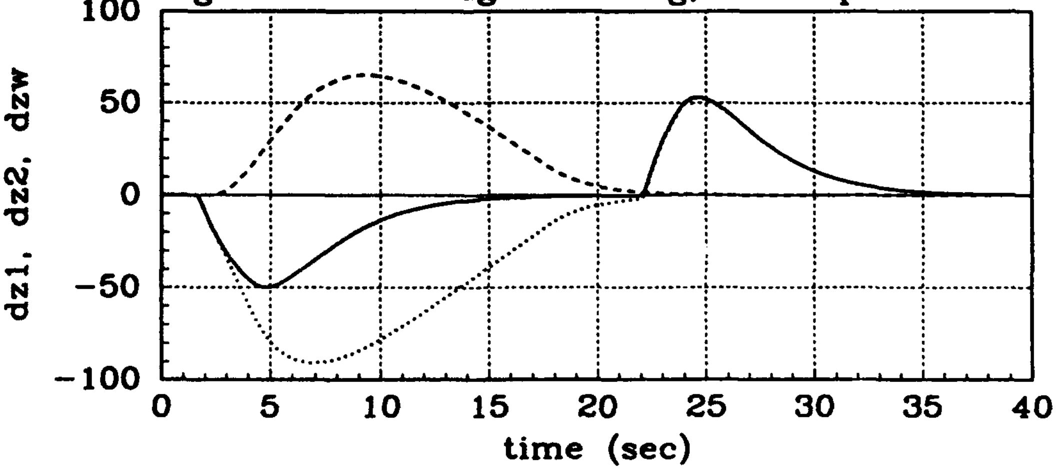


Figure B-26: Ridge Crossing, dz resp

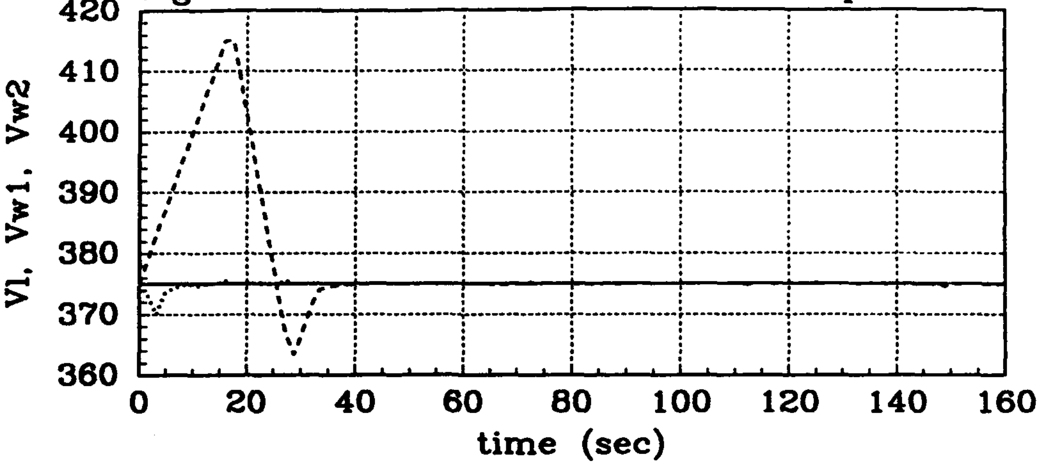


Figure B-27: Trail to Diamond, V resp

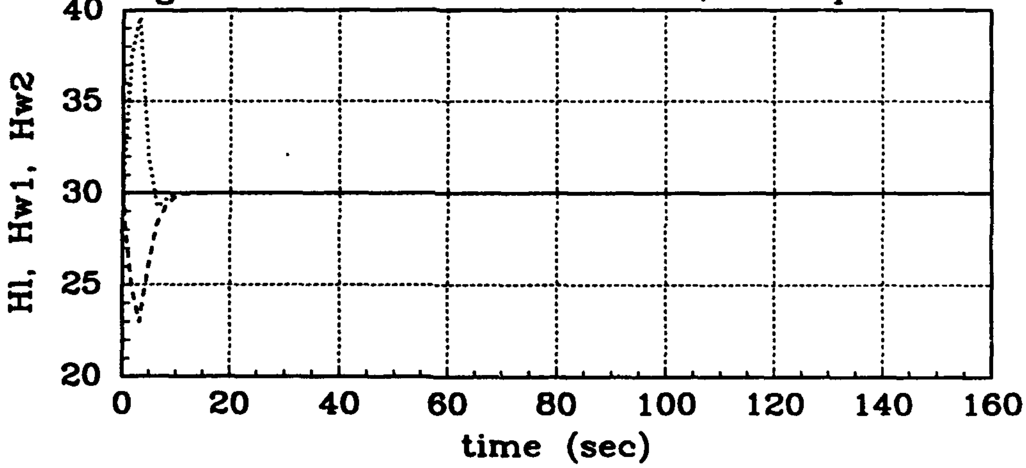


Figure B-28: Trail to Diamond, H resp

Figure B-29: Trail to Diamond, dx resp

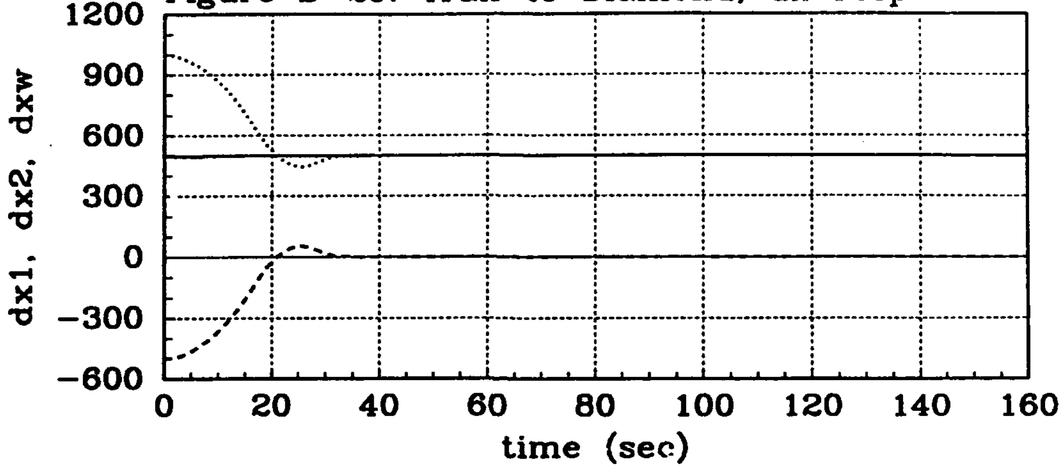


Figure B-30: Trail to Diamond, dy resp

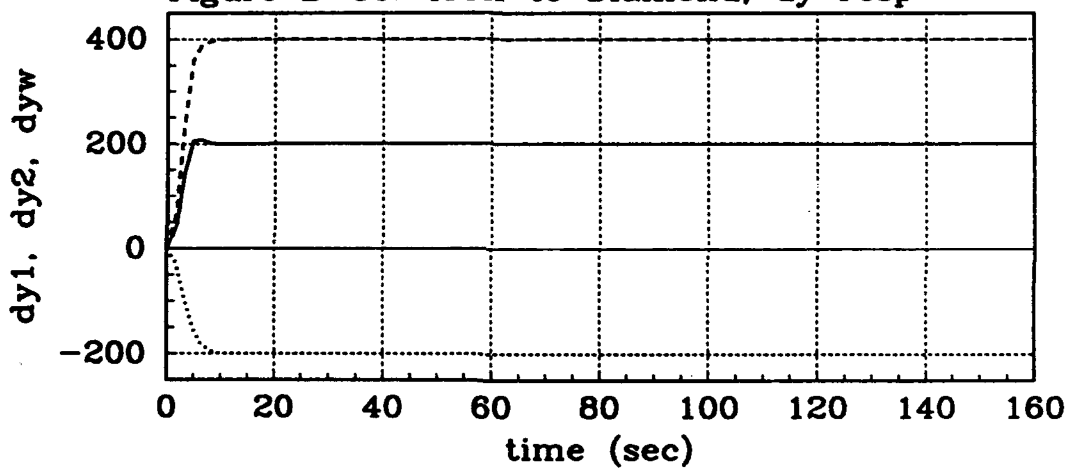
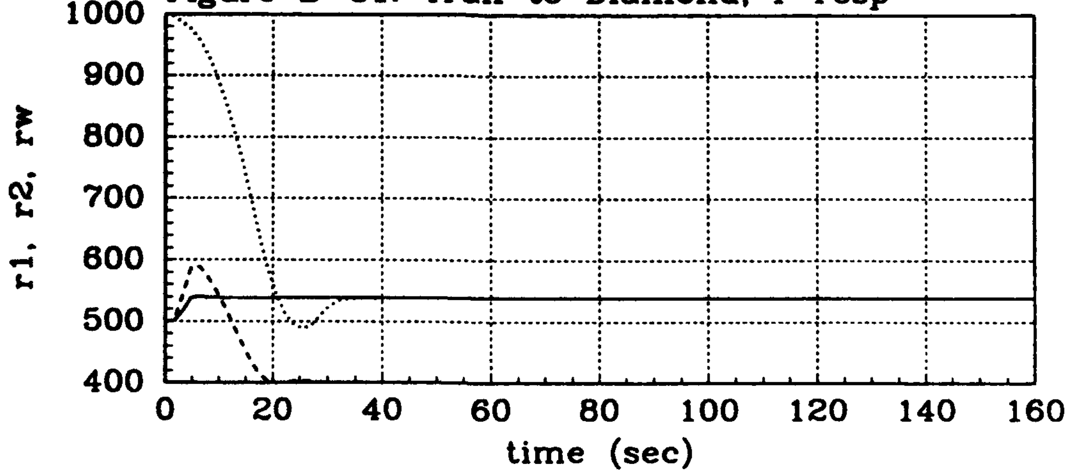


Figure B-31: Trail to Diamond, r resp



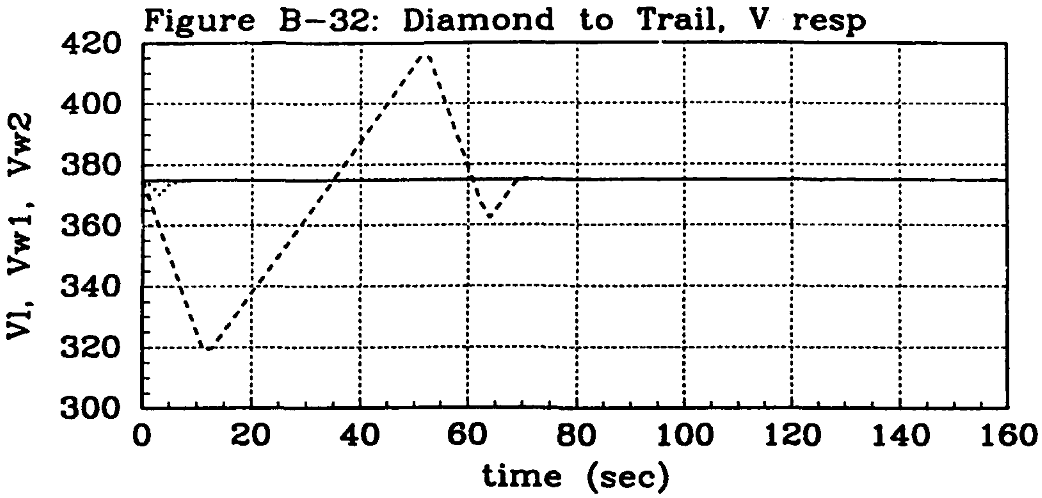


Figure B-32: Diamond to Trail, V resp
Vl, Vw1, Vw2
420
400
380
360
340
320
300
0
20
40
60
80
100
120
140
160
time (sec)

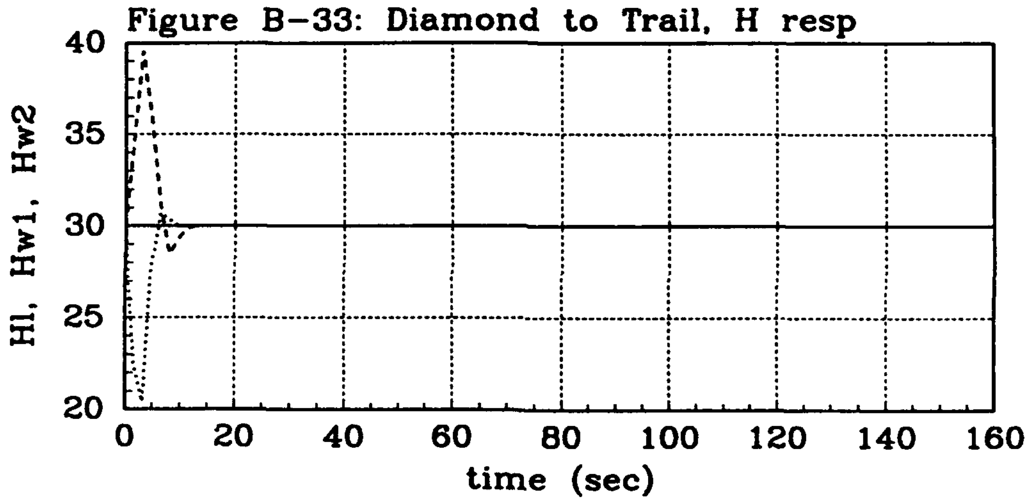


Figure B-33: Diamond to Trail, H resp
Hl, Hw1, Hw2
40
35
30
25
20
0
20
40
60
80
100
120
140
160
time (sec)

Figure B-34: Diamond to Trail, dx resp

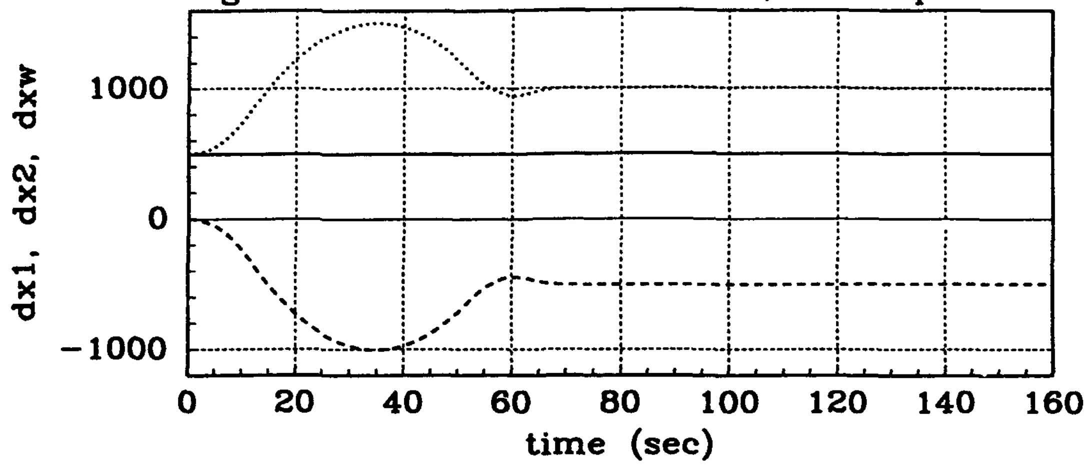


Figure B-35: Diamond to Trail, dy resp

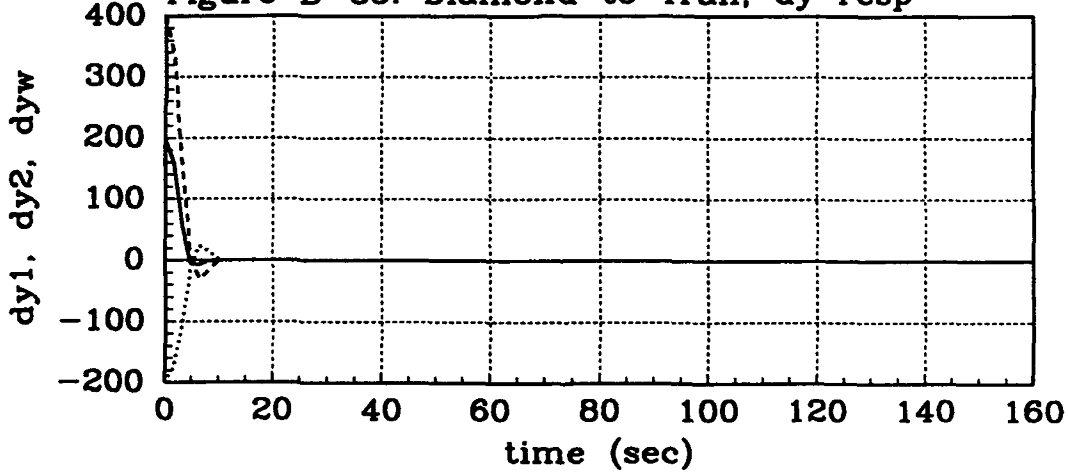
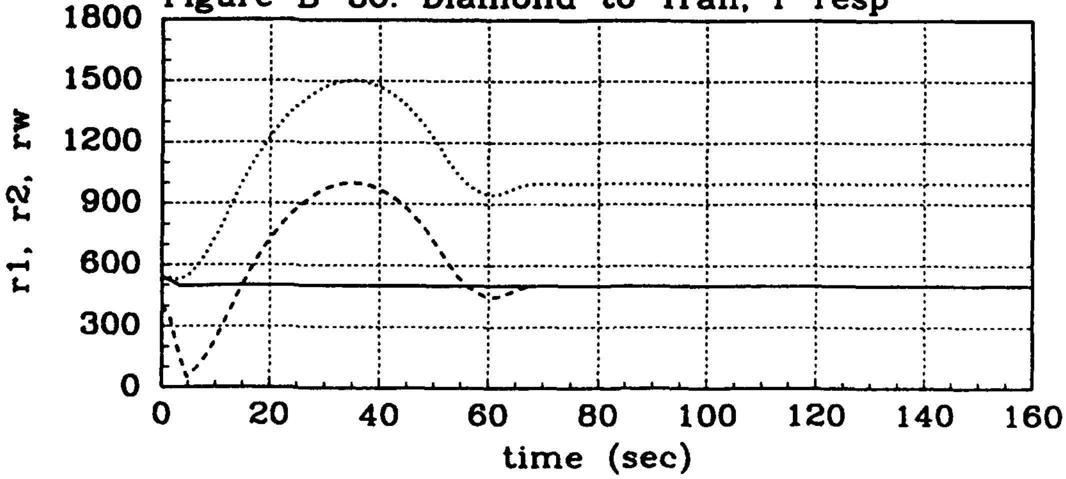


Figure B-36: Diamond to Trail, r resp



Appendix C: Controlled Helicopter Formation System Responses

This appendix contains plots depicting the performance of the complete, controlled formation control system with H-53 helicopter models inserted in place of C-130 models. The formation model used for all plots has a lead and wing #1 helicopter of like capabilities, and a wing #2 which is less capable in terms of maneuvering capabilities (F4) in the report. Plots contained in this appendix are arranged as follows.

Legend For All Plots

1st parameter :	Solid Line (----------)
2nd parameter :	Dotted Line (············)
3rd parameter :	Dashed Line (- - - - -)

Figure C-1: F4-H: V input-V resp

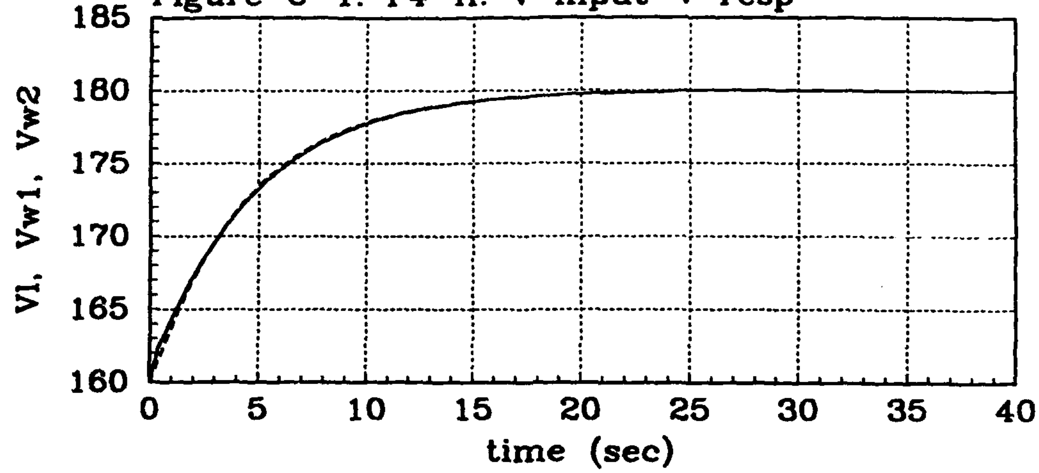


Figure C-2: F4-H: V input-dx resp

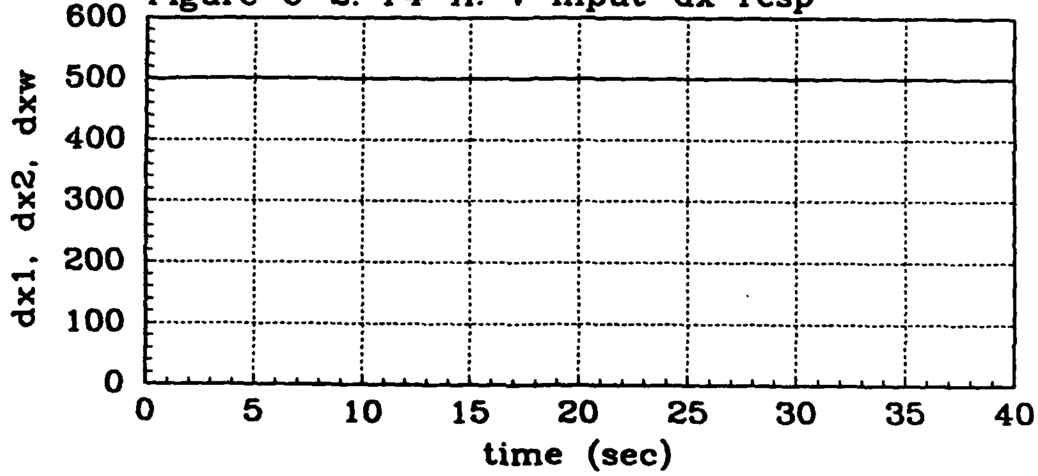
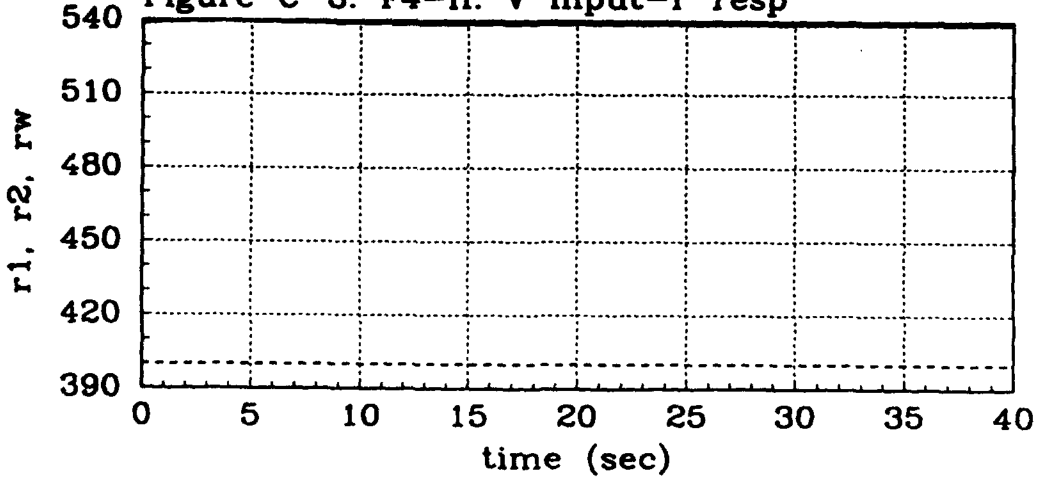


Figure C-3: F4-H: V input-r resp



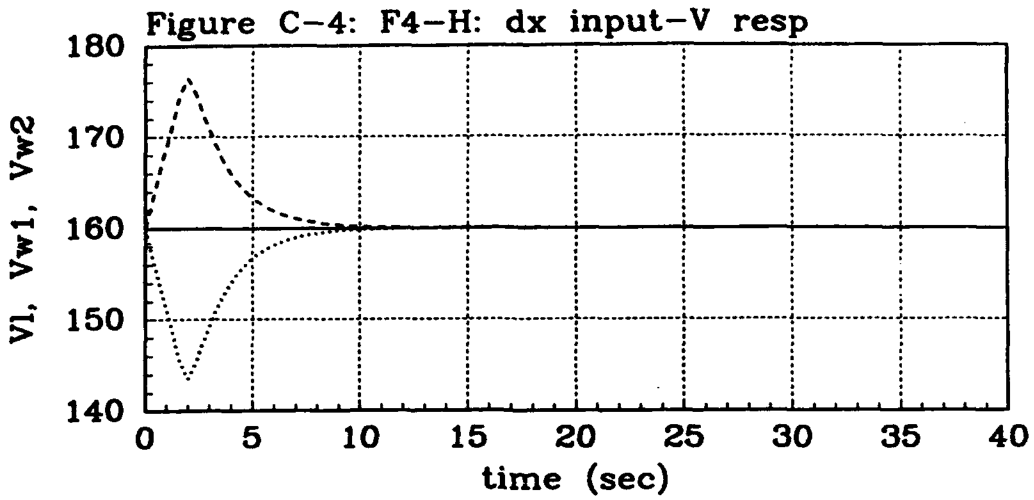


Figure C-4: F4-H: dx input-V resp
Vl, Vw1, Vw2
180
170
160
150
140
0
5
10
15
20
25
30
35
40
time (sec)

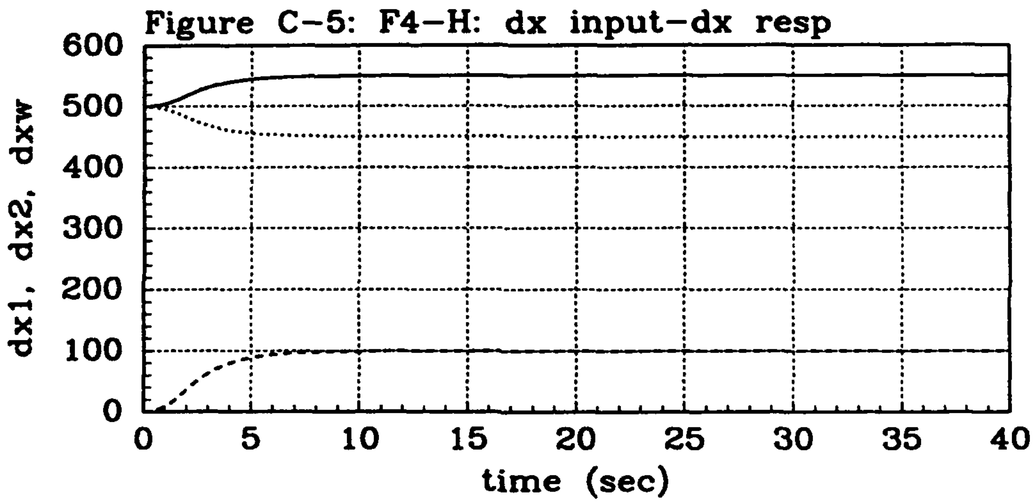


Figure C-5: F4-H: dx input-dx resp
dx1, dx2, dxw
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
time (sec)

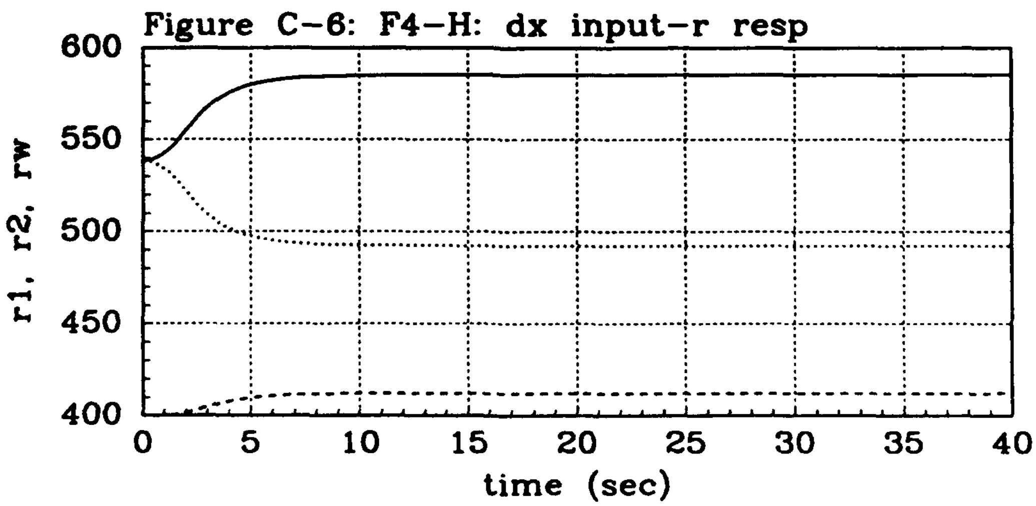


Figure C-6: F4-H: dx input-r resp
r1, r2, rw
600
550
500
450
400
0
5
10
15
20
25
30
35
40
time (sec)

Figure C-7: F4-H: H input-H resp

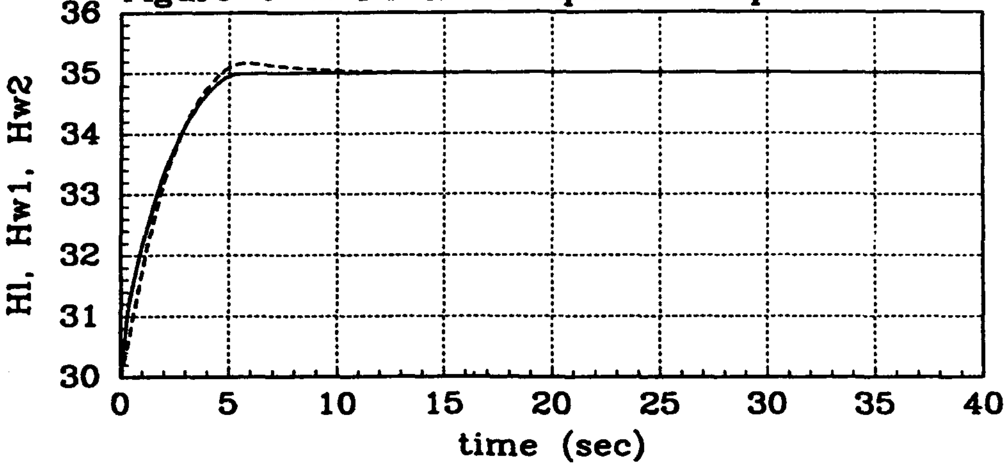


Figure C-8: F4-H: H input-dy resp

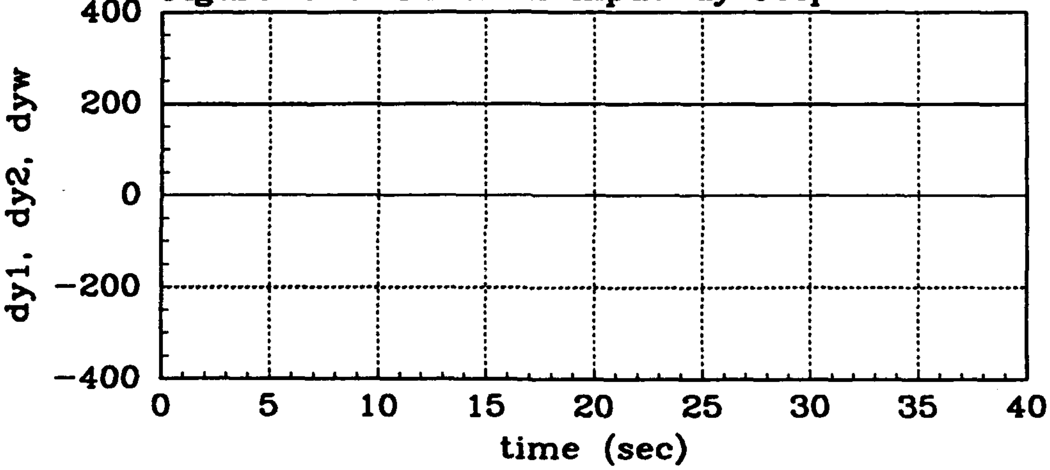


Figure C-9: F4-H: H input-r resp

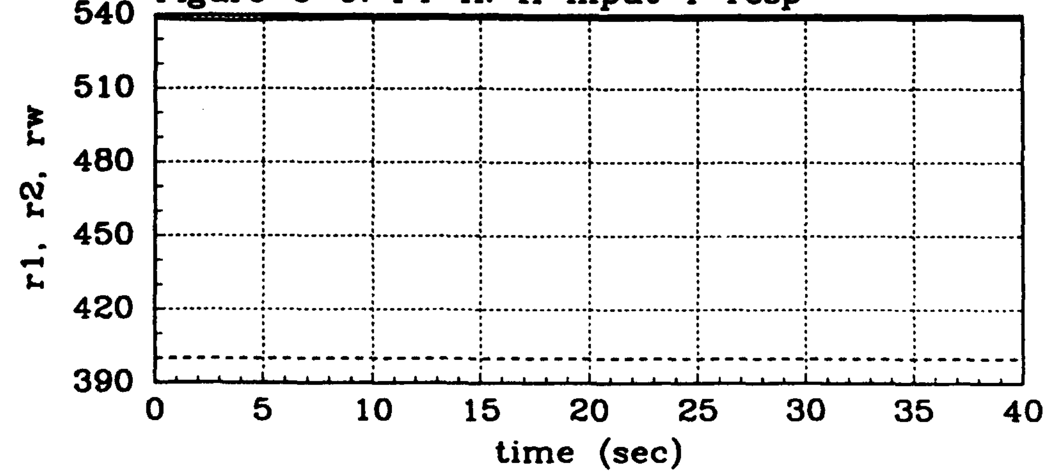


Figure C-10: F4-H: dy input-H resp

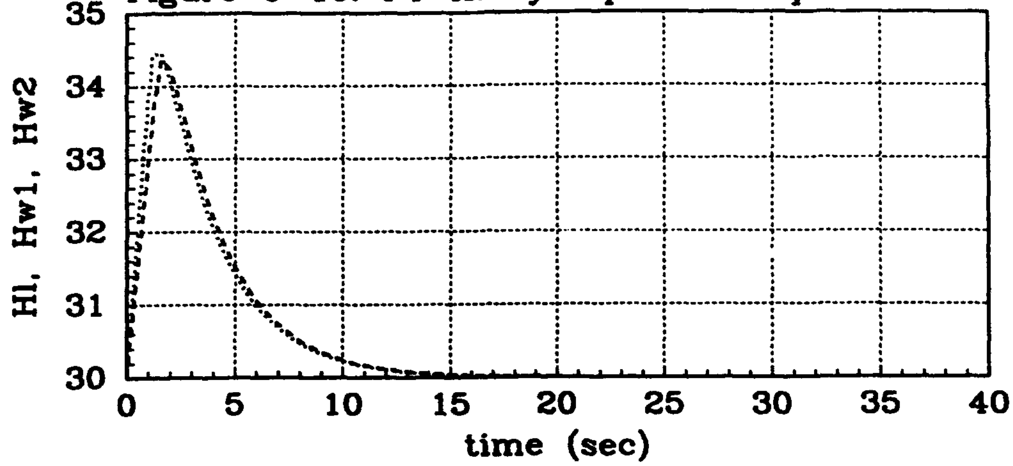


Figure C-11: F4-H: dy input-dy resp

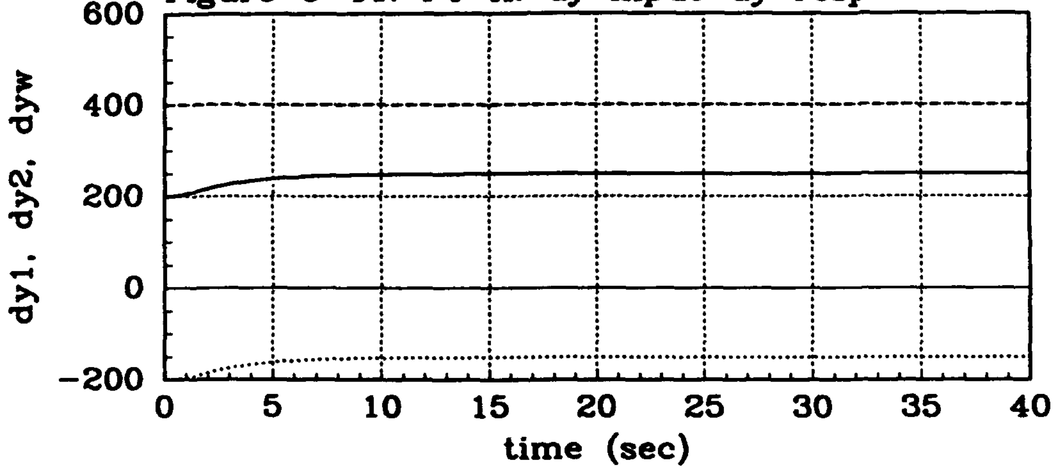


Figure C-12: F4-H: dy input-r resp

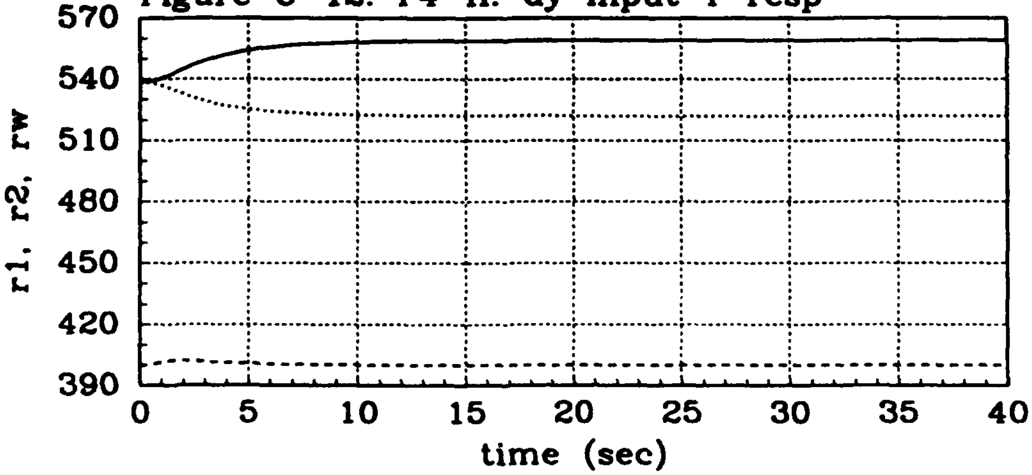


Figure C-13: F4-H: A input-A resp

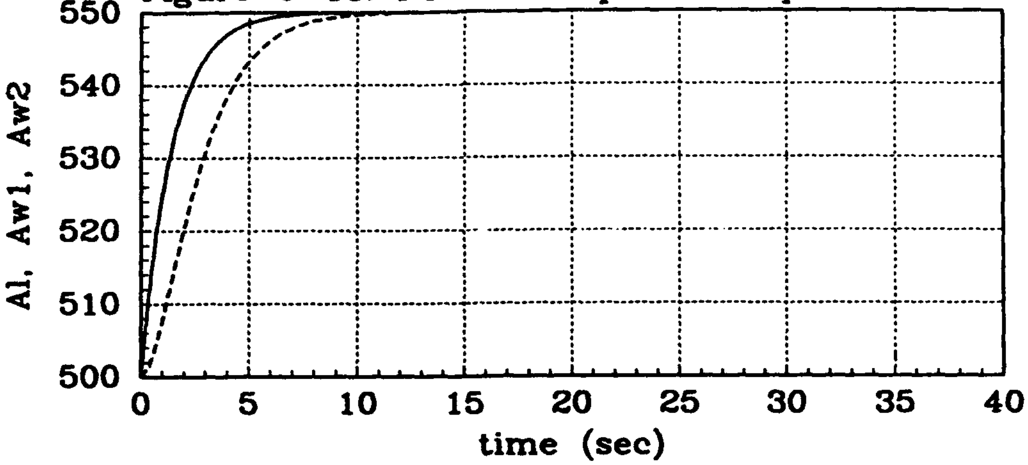


Figure C-14: F4-H: A input-dz resp

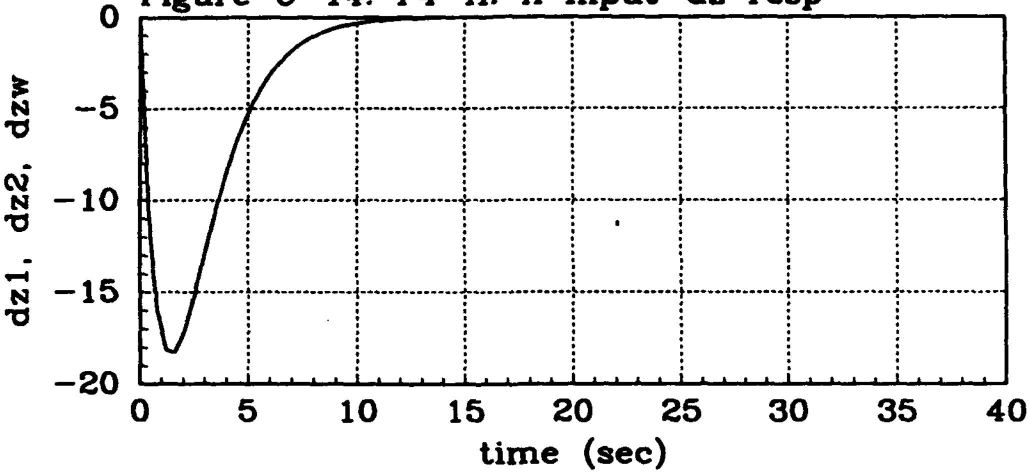


Figure C-15: F4-H: A input-r resp

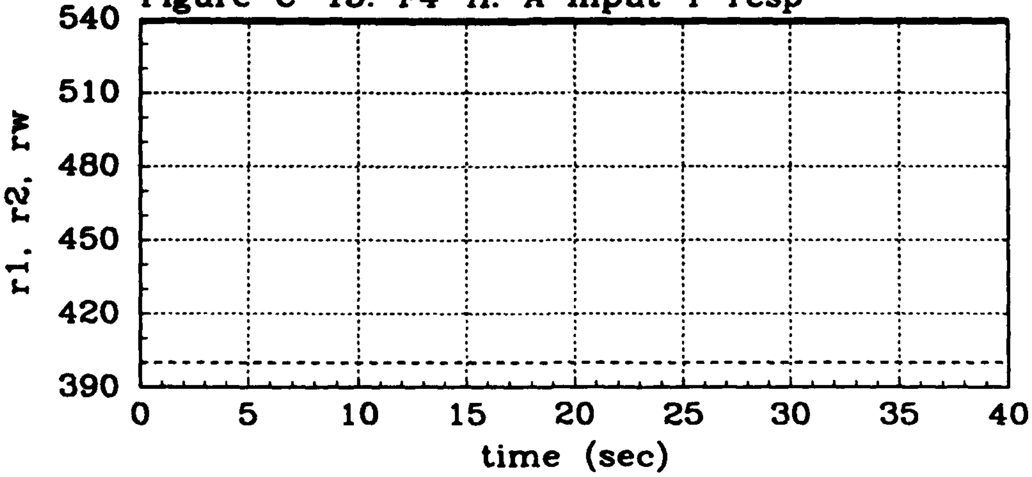


Figure C-16: F4-H: dz input-A resp

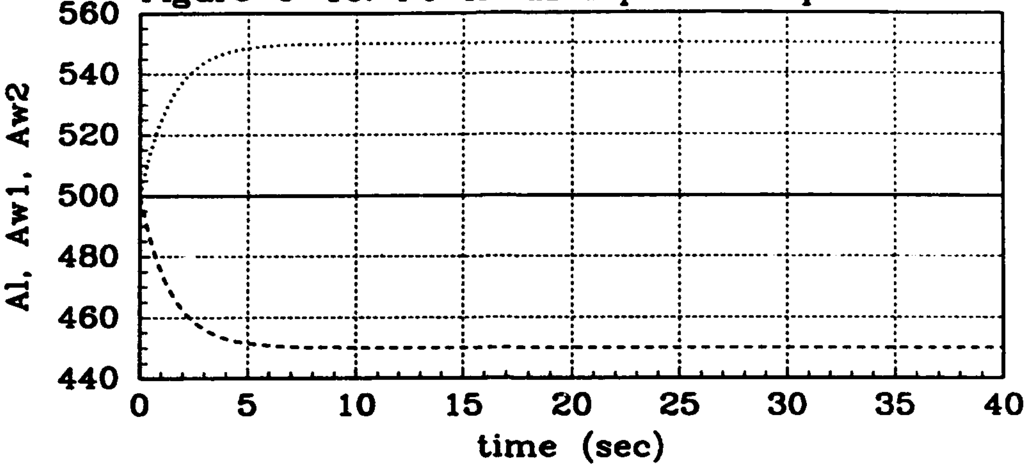


Figure C-17: F4-H: dz input-dz resp

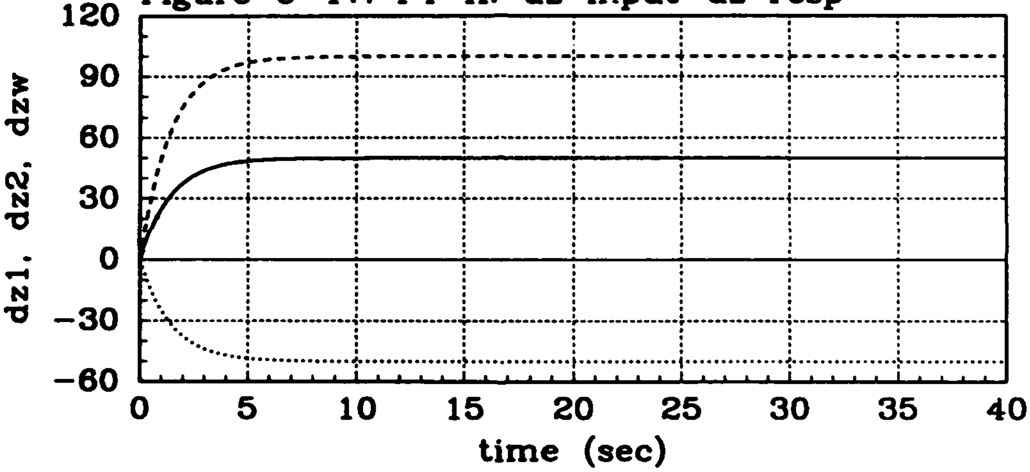


Figure C-18: F4-H: dz input-r resp

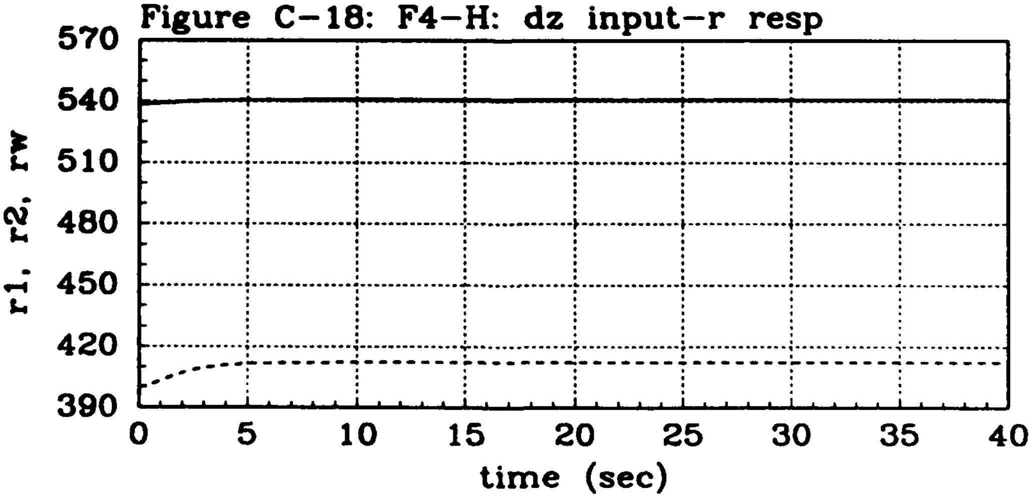


Figure C-19: H-Flat Turn, V Response

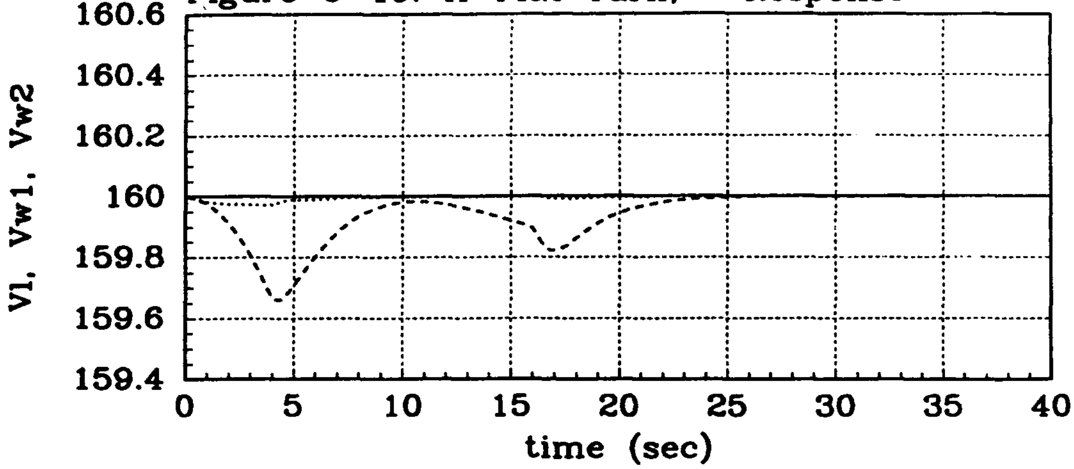


Figure C-20: Helo-Flat Turn, dx Response

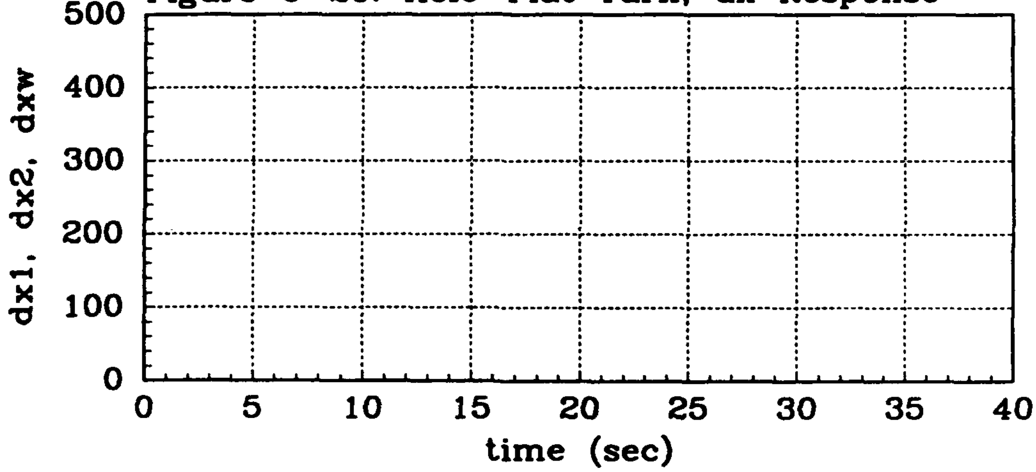


Figure C-21: Helo-Flat Turn, H Response

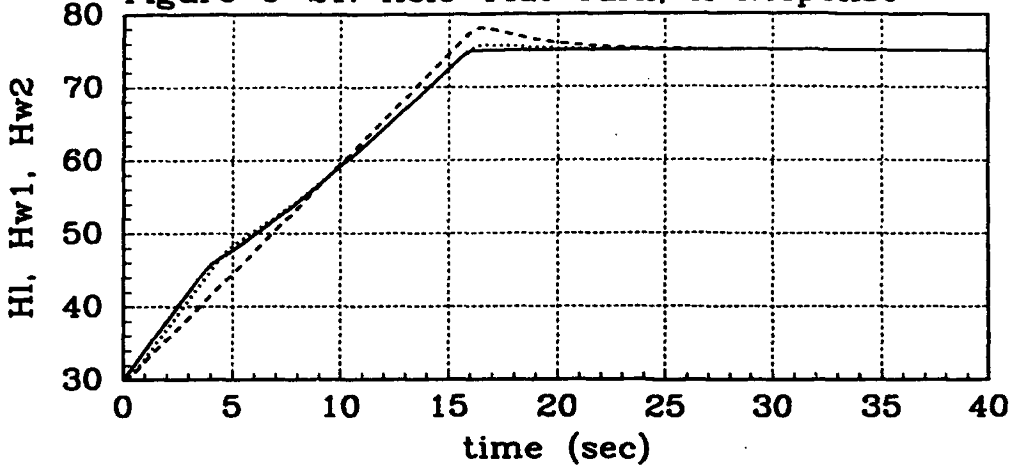


Figure C-22: Helo-Flat Turn, dy Response

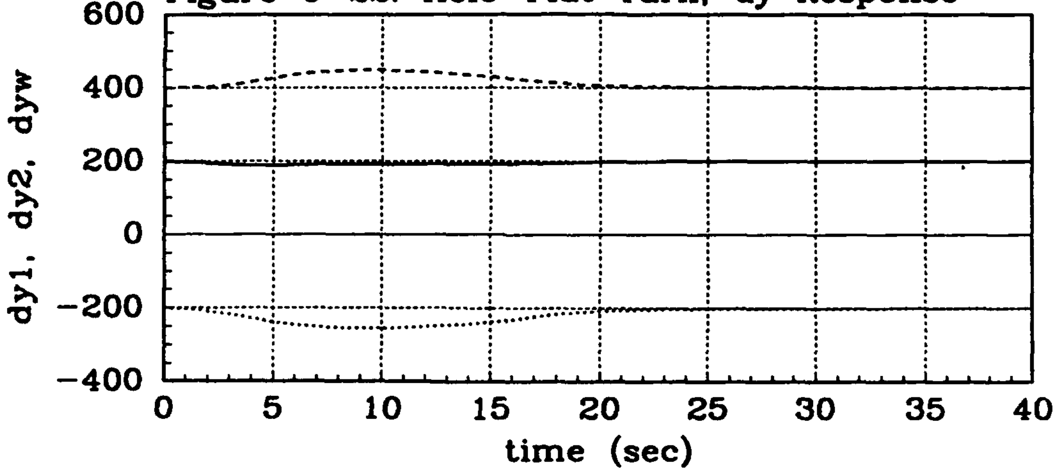
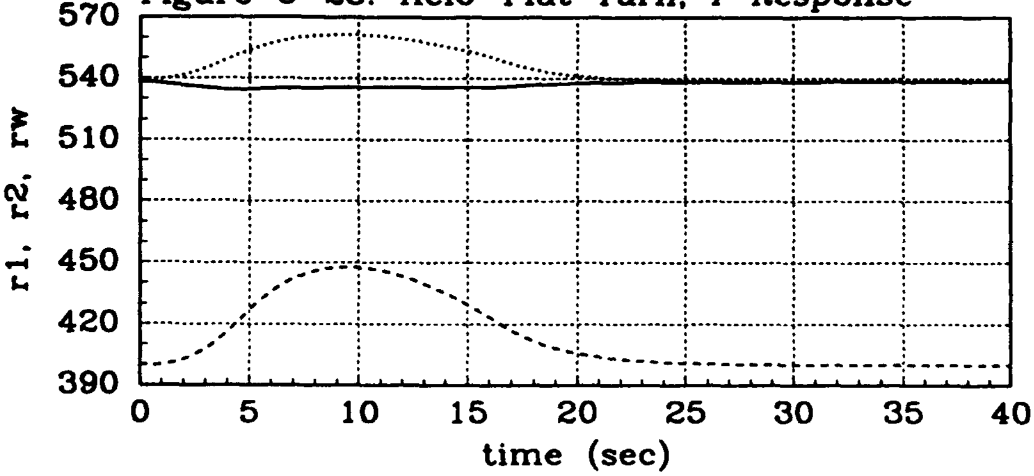


Figure C-23: Helo-Flat Turn, r Response



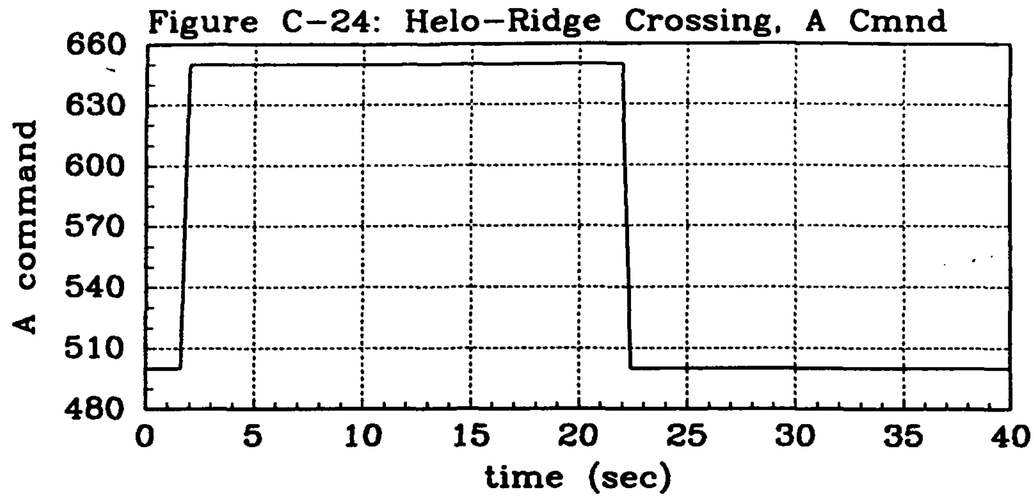


Figure C-24: Helo-Ridge Crossing, A Cmnd
660
630
600
570
540
510
480
A command
0
5
10
15
20
25
30
35
40
time (sec)

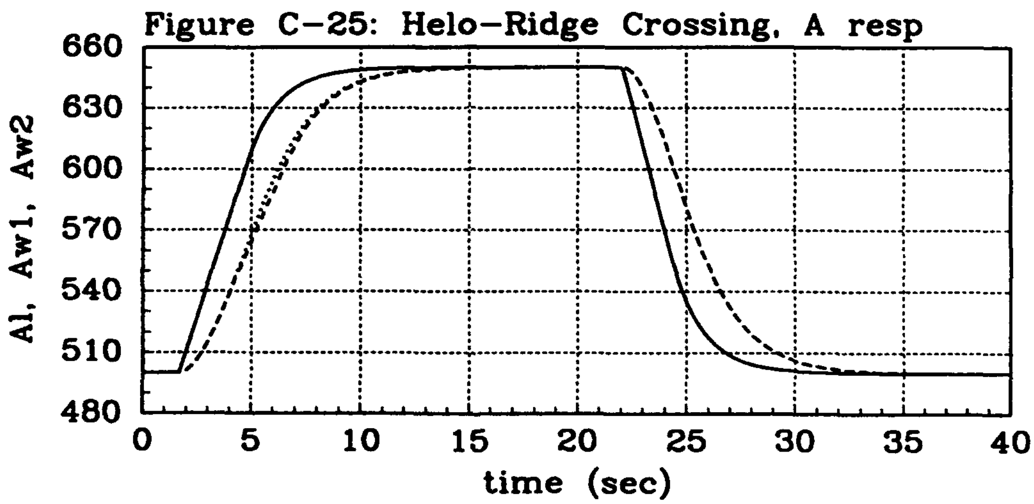


Figure C-25: Helo-Ridge Crossing, A resp
660
630
600
570
540
510
480
Al, Aw1, Aw2
0
5
10
15
20
25
30
35
40
time (sec)

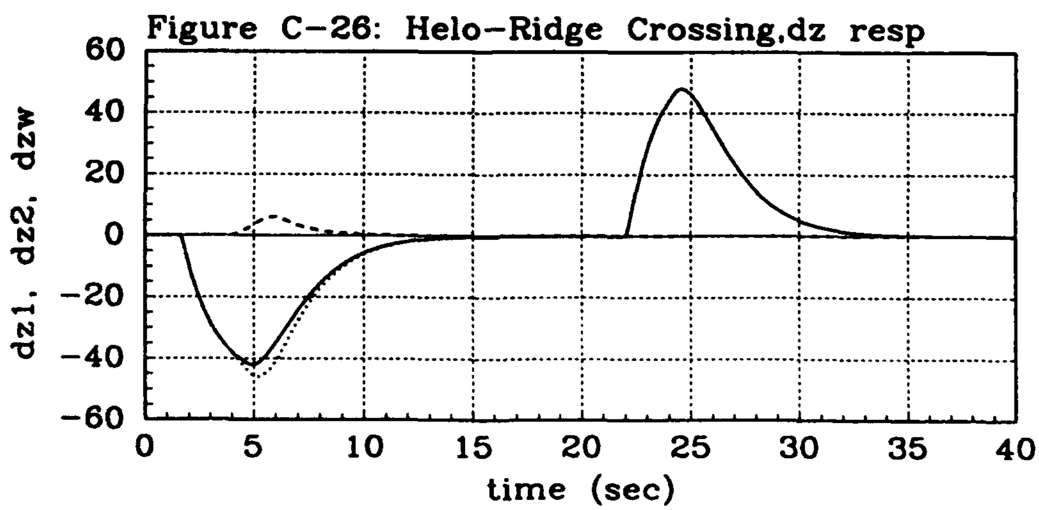


Figure C-26: Helo-Ridge Crossing,dz resp
60
40
20
0
−20
−40
−60
dz1, dz2, dzw
0
5
10
15
20
25
30
35
40
time (sec)

Figure C-27: H-Trail to Diamond, V resp

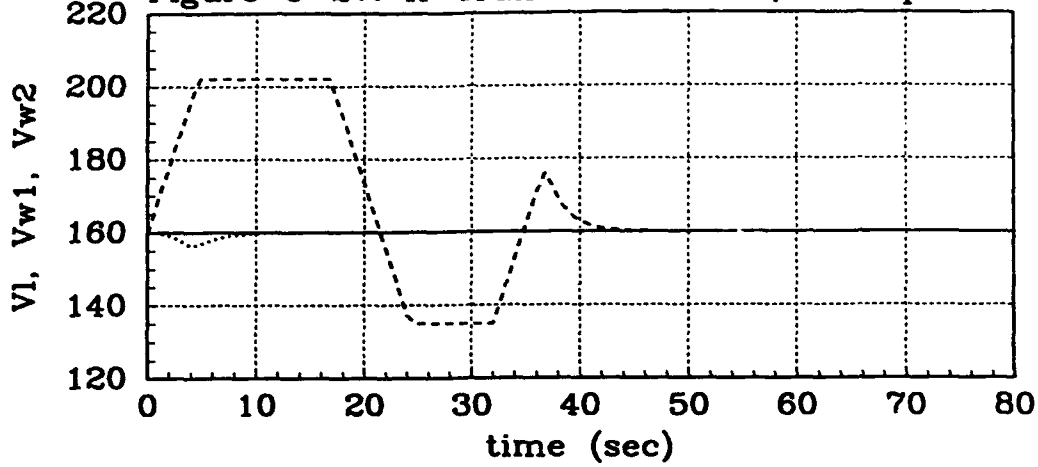
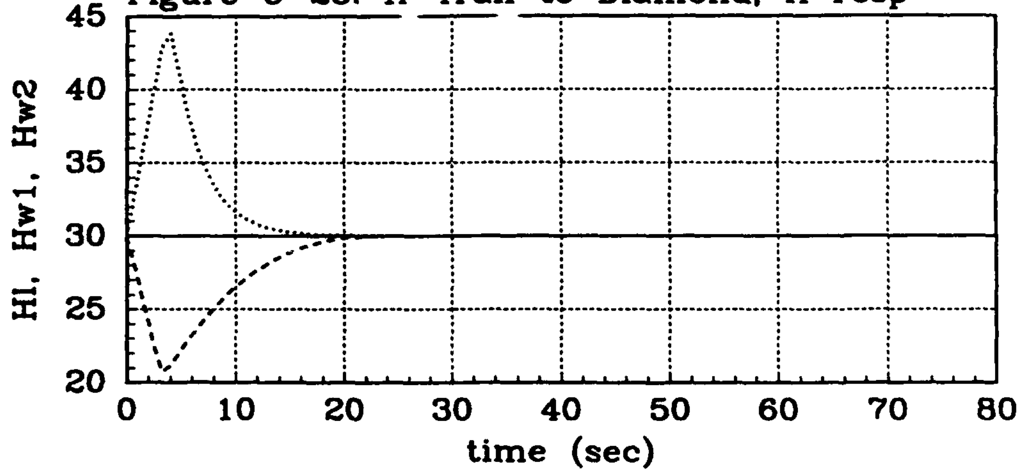


Figure C-28: H-Trail to Diamond, H resp



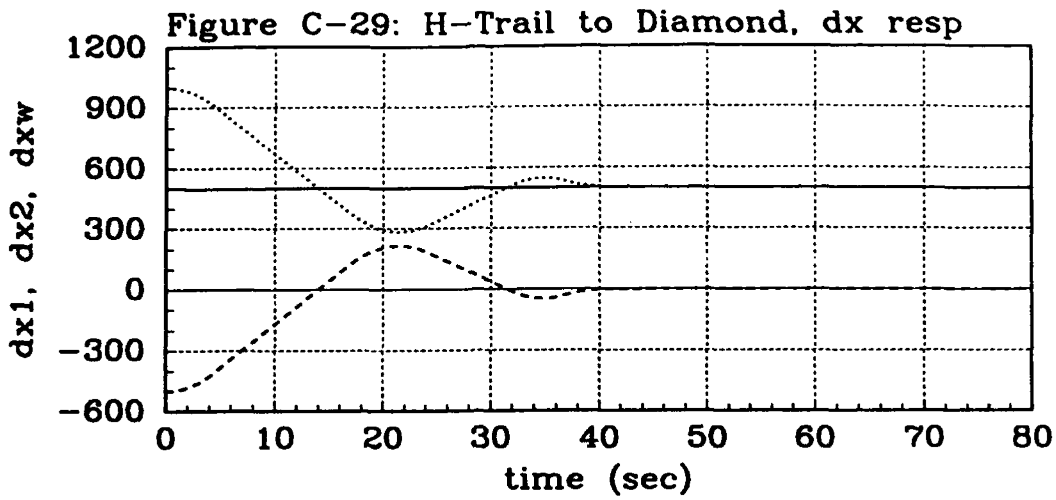


Figure C-29: H-Trail to Diamond, dx resp
1200
900
600
300
0
-300
-600
dx1, dx2, dxw
0
10
20
30
40
50
60
70
80
time (sec)

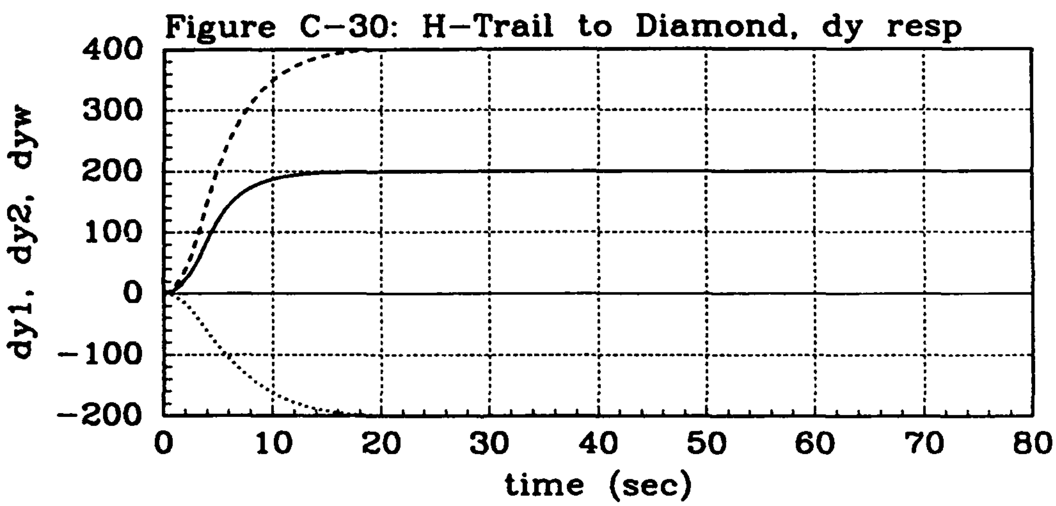


Figure C-30: H-Trail to Diamond, dy resp
400
300
200
100
0
-100
-200
dy1, dy2, dyw
0
10
20
30
40
50
60
70
80
time (sec)

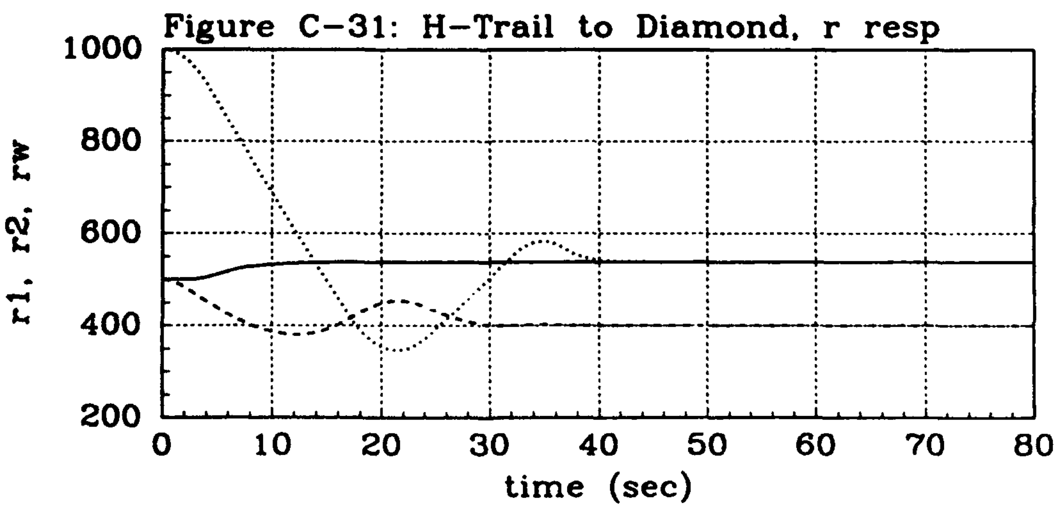


Figure C-31: H-Trail to Diamond, r resp
1000
800
600
400
200
r1, r2, rw
0
10
20
30
40
50
60
70
80
time (sec)

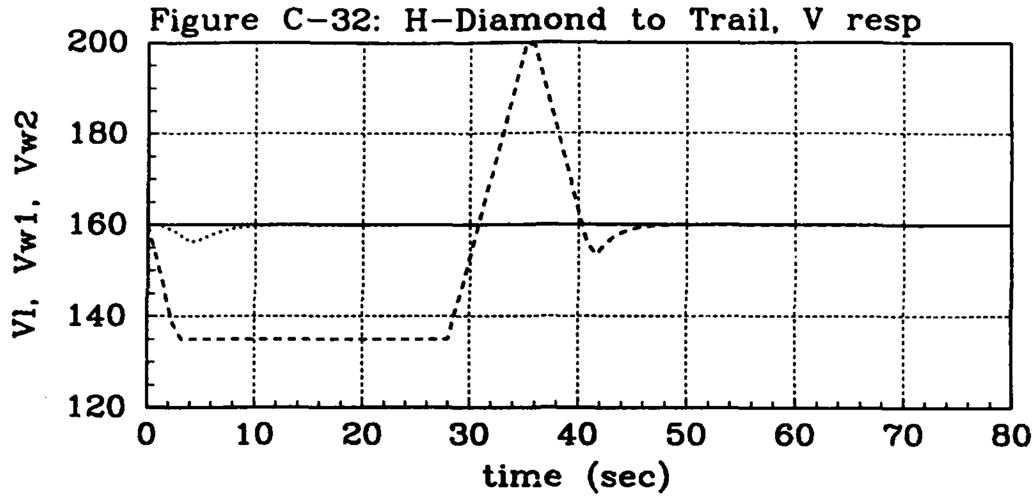


Figure C-32: H-Diamond to Trail, V resp
200
180
160
140
120
Vl, Vw1, Vw2
0
10
20
30
40
50
60
70
80
time (sec)

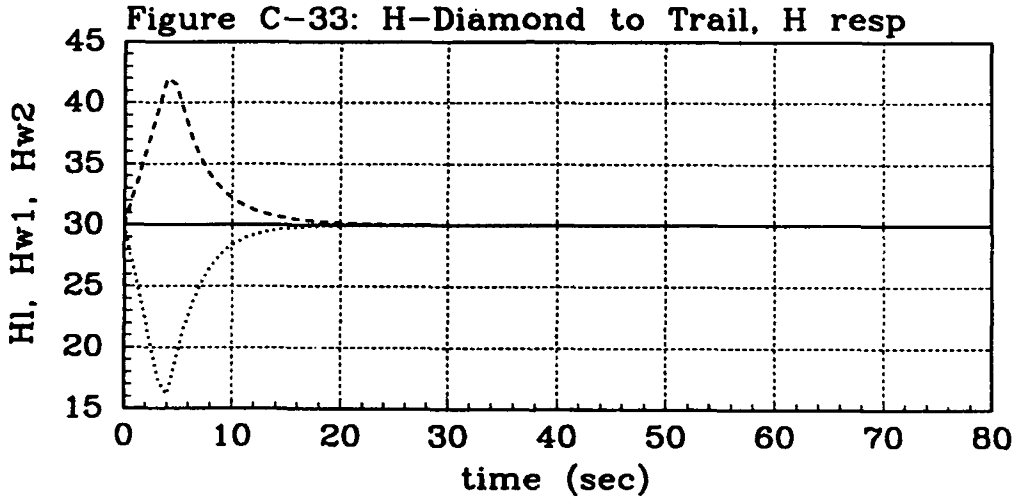


Figure C-33: H-Diamond to Trail, H resp
45
40
35
30
25
20
15
Hl, Hw1, Hw2
0
10
20
30
40
50
60
70
80
time (sec)

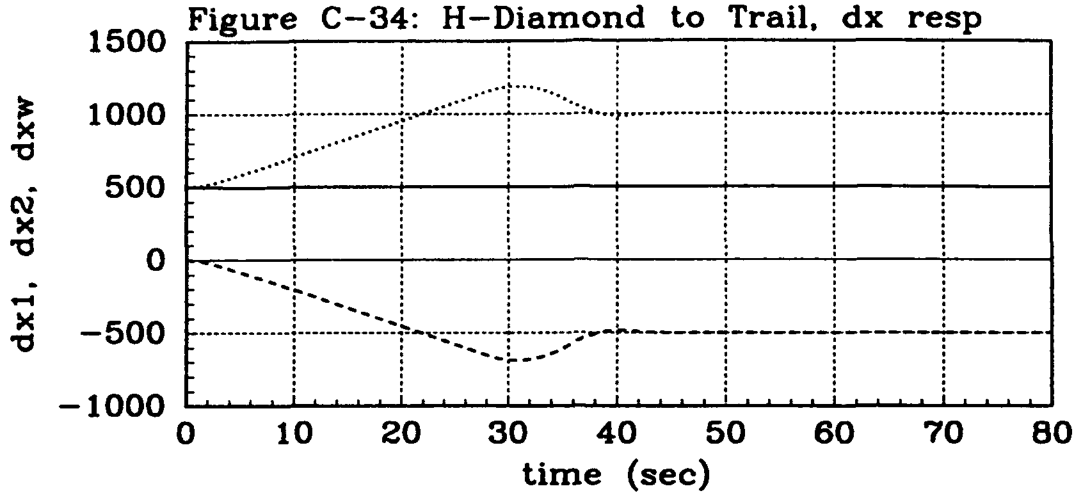


Figure C-34: H-Diamond to Trail, dx resp
dx1, dx2, dxw
1500
1000
500
0
-500
-1000
0
10
20
30
40
50
60
70
80
time (sec)

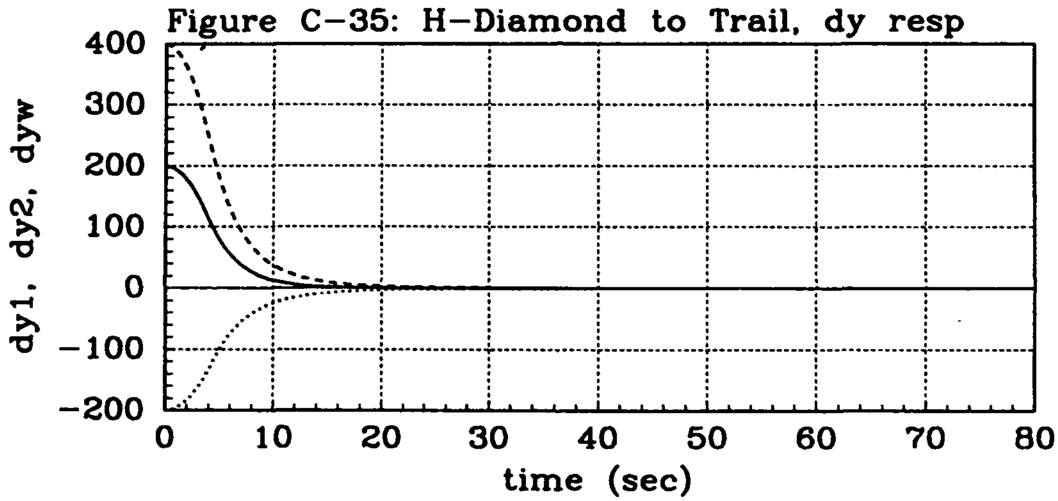


Figure C-35: H-Diamond to Trail, dy resp
dy1, dy2, dyw
400
300
200
100
0
-100
-200
0
10
20
30
40
50
60
70
80
time (sec)

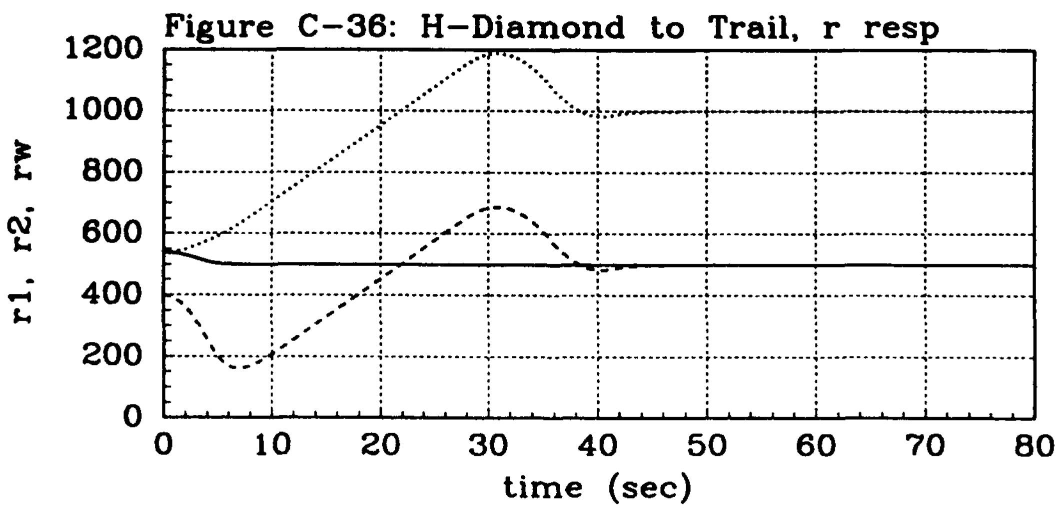


Figure C-36: H-Diamond to Trail, r resp
r1, r2, rw
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
80
time (sec)

BIBLIOGRAPHY

1. Ballantyne, Frank P. and Donn A. Allen. Visionics and Human Factors Analysis for Helicopter Night Formation Flight: Final Report, February 1970. Contract DAAB07-69-C-0220. Culver City CA: Hughes Aircraft Company, Aeronautical Systems Division, February 1970 (AD507282).

2. Barfield, A. Finley. Multivariable Control Laws for the AFTI/F-16. MS thesis, AFIT/GE/EE/83S-4. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, July 1983.

3. Barfield, A. Finley. Senior Flight Control Engineer, Flight Controls Division, Air Force Flight Dynamics Laboratory. Personal interviews. Wright Research and Development Center, Wright-Patterson AFB OH, June 1990 - March 1991.

4. Blakelock, John H. Automatic Control of Aircraft and Missiles. New York: John Wiley & Sons, Inc., 1965.

5. Bradshaw, A. and B. Porter. Singular perturbation methods in the design of tracking systems incorporating fast-sampling error-activated controllers, *International Journal of Systems Science, 12, Number 10:* 1181-1191 (1981).

6. D'Azzo, John J. and Constantine H. Houpis. Linear Control System Analysis and Design, 3rd Ed. New York: McGraw-Hill Book Company, 1988.

7. Etkin, Bernard. Dynamics of Atmospheric Flight. New York: John Wiley & Sons, Inc., 1972.

8. Gill, Robert, Chief Engineer, Intraformation Positioning System Program, Flight Controls Division, Air Force Flight Dynamics Laboratory. Personal interviews. Wright Research and Development Center, Wright-Patterson AFB OH, June 1990 - March 1991.

9. Gray, Clifford M. et al. The Drone Formation Control System. International Business Machine (IBM). Undated.

10. Hartley, Gerald A. Automatic Formation Control of Full-Scale Aircraft Targets, September 1985. Naval Weapons Center Technical Publication 6670. Naval Weapons Center, China Lake CA 93555-6001 (AD-B097 424).

11. Heffley, Robert K. et al. A Compilation and Analysis of Helicopter Handling Qualities Data: Volume 1: Data Compilation, August 1979. NASA Contractor Report 3144, Contract Number NAS2-9344. Mountain View CA: Systems Technology, Inc., August 1979.

12. Heffley, Robert K. et al. A Compilation and Analysis of Helicopter Handling Qualities Data: Volume 2: Data Analysis, August 1979. NASA Contractor Report 3144, Contract Number NAS2-9344. Mountain View CA: Systems Technology, Inc., August 1979.

13. Lockheed, Aeronautical Systems Division. C-130 Aircraft Stability and Control Data. Provided by Mr J. M. McCarty, Lockheed, Aeronautical Systems Division, Marrietta GA, 4 October 1990.

14. Porter, B. and A. Bradshaw. Singular perturbation methods in the design of tracking systems incorporating high-gain error-activated controllers, *International Journal of Systems Science, 12, Number 10:* 1169-1179 (1981).

15. Prouty, Raymond W. Helicopter Performance, Stability, and Control. Boston: PWS Publishers.,1986.

16. United States Air Force. AC-130H Spectre. Fact Sheet. 1st Special Operations Wing, Public Affairs Division, (MAC), Hurlburt Field, FL, December 1989.

17. United States Air Force. HC-130P/N. Fact Sheet. 1st Special Operations Wing, Public Affairs Division, (MAC), Hurlburt Field, FL, February 1989.

18. United States Air Force. MC-130E Combat Talon. Fact Sheet. 1st Special Operations Wing, Public Affairs Division, (MAC), Hurlburt Field, FL, December 1988.

19. United States Air Force. MH-53H Pave Low Helicopter. Fact Sheet. 1st Special Operations Wing, Public Affairs Division, (MAC), Hurlburt Field, FL, February 1987.

20. Wellinger, D. et al. Army Formation Flight Study: Final Report, Report Number 6, 1 July 1964 to 26 February 1965. Contract Number DA-36-039-AMC-03367(E), 1E1-20601-A-219-03. Burlington, Massachusetts: Radio Corporation of America, Defense Electronic Products, Aerospace Systems Division, February 1965 (478441).

21. Wright Research and Development Center, Aeronautical Systems Division, Air Force Systems Command. Intraformation Positioning System (IFPS) Request For proposal, Number F33615-89-R-3605. Wright-Patterson AFB, OH, 14 December 1990.

Vita

Captain Paul R. Rohs was born on 19 April 1956 in Buffalo, New York. He grew up in the small town of Warsaw New York where he graduated from Warsaw High School in 1974. He enlisted in the Air Force in December of 1977, and was accepted into the Airman's Education and Commissioning Program in 1982. He attended Ohio State University and received a Bachelor of Science in Aeronautical and Astronautical Engineering in June of 1985. Upon completion of Officer's Training School, he received a commission in the USAF and was assigned to the Flight Dynamics Laboratory at Wright-Patterson Air Force Base. While at the Flight Dynamics Laboratory, he was assigned to the design branch of the Technology Assessment Division where he developed Hypersonic Aerodynamics analysis capabilities and performed aerodynamic analysis on the National Aerospace Plane contractor configurations. In 1987, he was assigned to the Advanced Fighter Technology Integration (AFTI) /F-16 Advanced Development Program Office as the Director of Test and Evaluation for Close Air Support flight test operations. He entered the School of Engineering, Air Force Institute of Technology, in may 1989.

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